HUMAN-ENVIRONMENT RELATIONSHIPS IN DRYLANDS – WITH A FOCUS ON THE WEST AFRICAN SAHEL

by

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ABSTRACT

The study of human-environment relationships in drylands, a topic that has engaged scientists for many decades, has captured new interest since satellite observations of land cover change over time became widely available. Particularly interpretations of the nature, extent and causation of desertification - or land degradation in drylands - have been influenced by the availability of more and more extensive time series of satellite observations.

This dissertation reviews some three decades of debate on the problem of desertification by examining advances in four disciplinary contexts in which these debates have evolved: our understanding of climate, ecology, social and political processes. Changes over time in these contexts have significantly influenced the direction of the desertification debate and created some controversy.

The respective roles that climate and human factors might have played in causing or sustaining environmental changes are then explored at the example of the West African Sahel region. Linear regression of time series of remotely sensed vegetation greenness data against rainfall data reveals where and to which extent trends in vegetation greenness are determined by rainfall, and, conversely, where other factors are likely to have played a significant role. While the results of the remote sensing study point to areas in which the impact of human factors is likely to have modified the simple rainfall-vegetation connection, claims of widespread human-induced desertification at a regional scale are challenged.

CHAPTER 1

INTRODUCTION

Background

The idea for this dissertation sprang from a Workshop on Changes in the Sahel that was held in Nairobi in October 2003 with the aim of synthesizing research results over the past 20 years and evaluating recent changes in the region. The workshop convened some 15 invited experts who had conducted significant research on the Sahel as well as representatives of major international organizations who work in the region. Due to my keen interest in the issues at work in the Sahel, I was given the opportunity to participate in this event as a student observer and to prepare a background paper. One of the outcomes of the workshop related to uncertainties in the interpretation of a recently observed trend of increasing vegetation greenness throughout the Sahel, which has been accompanied by an increase in rainfall. Caution is warranted as to the interpretation of this phenomenon as "recovery", as it is neither expected to continue, nor necessarily represents a return to a previous vegetation composition. Part of the uncertainties arise from the fact that cause-and-effect relationships among climate, vegetation cover, and land use and management are still incompletely understood, and have been interpreted differently over time. The desertification debate has captured scientific and policy interest since the West African Sahel region was hit by a series of drought years in the late 1960s and 70s and illustrates how different, and sometimes contrary, interpretations of the human-environment interactions have evolved.

This dissertation examines the respective roles that climate and human factors might have played in causing or sustaining the environmental changes observed in the Sahel as well as how our understanding of these roles has been shaped by a continuously evolving scientific framework. It encompasses three inter-related topics pertaining to the Sahel in particular and to drylands in general: variability in rainfall and resource base, land degradation, and adaptive land use and management.

Drylands, and particularly the Sahel region, provide an example of where land use policies and management practices have been largely uninformed by scientific findings. Efforts to combat desertification have arguably been driven more by the politics of institutions than by science. Partly, this predicament might be explained by insufficient or inadequate communication between scientists and policy makers. Therefore, while parts of this dissertation are addressed to an academic audience and presented as scientific papers (Appendices A, C and D), other parts are primarily written for decision-makers in a non-technical language, however with the scientific rigor appropriate of scholarly research and publication (Appendices B and E).

Research questions and approach

The overarching questions guiding this research are: What are the respective roles that climate and human factors play in land cover and vegetation change in drylands? And, how can we disentangle them? These questions are broken down as follows:

The overall framework is set by the first two publications. The first (Appendix A) takes an historical perspective and reviews some three decades of debate on the problem of desertification, or land degradation in drylands, by examining advances in four disciplinary contexts in which these debates have evolved: our understanding of climate, ecology, social and political processes. Changes over time in these contexts have significantly influenced the direction of the desertification debate and created some controversy. The second publication (Appendix B) outlines the current state of this debate, points out gaps in our understanding of the functioning of arid environments, elaborates on the linkages between land degradation, drought and desertification, and argues against the popular understanding of desertification as being a result primarily of adverse human impacts.

The third publication (Appendix C) is a regional-scale remote sensing-based study, which explores the influence of one of many factors, rainfall variability, on vegetation dynamics in the Sahel. Using monthly spatio-temporal datasets of rainfall and vegetation greenness, its goal was to identify spatial pattern of trends in rainfall and vegetation during the time period from 1982 to 2003, when rainfall increased to an “average” level after the great droughts and a greening of the vegetation was observed throughout the Sahel – an observation that has frequently been used as evidence against the alleged extent of desertification. This study seeks to establish whether, where, and to what extent satellite observed vegetation greenness is indeed determined by rainfall and, conversely, where other factors are likely to have played a significant role.

The methodology developed to disentangle rainfall and other forcing factors of vegetation dynamics using remote sensing time series data, is further explored in a methodological study (Appendix D). The objective of this study was to test whether the rainfall-vegetation relationship established by means of coarse resolution datasets can be successfully transferred to finer resolution datasets.

A glance into the future is provided by the final part of this dissertation (Appendix E), which reviews trends and scenarios of several driving forces of change in deserts – population dynamics, demand for resources, climate variability and globalization – and assesses how the interplay of these driving forces is likely to impact future water availability, land degradation, and biodiversity in deserts (excluding the semiarid drylands). The approach taken in this chapter is more qualitative then quantitative, in order to avoid the uncertainties inherent in quantitative projections, particularly of complex phenomena. Proceeding from different possible scenarios, the chapter concludes with recommendations on sustainable resource management in deserts that would help the best case scenario to materialize.

Dissertation format

In agreement with policies of The University of Arizona Graduate College and the Arid Lands Resource Sciences PhD Program on the inclusion of published or publishable papers, this dissertation is presented in the form of two published journal papers, two peer-reviewed book chapters currently in print, and one conference proceedings paper. While the individual pieces necessarily constitute stand-alone contributions to different publications, in this dissertation they are joined by the broad theme of human-environment interactions in drylands as outlined in the previous section.

The first journal paper (Appendix A) on the desertification debate was prepared as a background paper for a United Nations Environment Programme (UNEP) workshop on Changes in the Sahel and subsequently published in a Special Issue of the *Journal of Arid Environments*. While the literature research and writing are entirely my own work, my co-author Chuck Hutchinson stirred my interest in the topic, suggested the structure of the paper, and edited the draft.

The next part (Appendix B) is an introductory chapter for a book on policy and governance issues and the implementation of the United Nations Convention to Combat Desertification (UNCCD). It was designed to provide the scientific background on the specifics of the dryland environment, its climatic challenges and the problem of land degradation. The involvement of my co-author Chuck Hutchinson was minimal and limited to editing of the draft.

The second journal paper (Appendix C), published in *Global Environmental Change*, is an empirical research paper that uses remotely sensed vegetation greenness and rainfall data to investigate spatial patterns of vegetation greenness and rainfall variability and their interrelationships in the Sahel. While I proposed the topic, designed and carried out the research during a summer internship at the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center, and wrote up the paper, my co-authors Assaf Anyamba and Compton Jim Tucker supervised my work, offered critical comments and edited the draft.

From this evolved a conference paper (Appendix D) written for the 31st International Symposium on Remote Sensing of Environment. It is a primarily methodological paper which tests the applicability of the previously established rainfall-vegetation greenness relationship to finer-scale datasets. Authorship is the same as in the previous paper, with the involvement of my co-authors Assaf Anyamba and Compton Jim Tucker limited to editing the final draft.

The dissertation ends with a paper written as a final chapter for the UNEP publication *Global Environmental Outlook for Deserts* (Appendix E) under lead authorship of myself and Chuck Hutchinson. The geographic scope of this last part differs from the previous parts in that it was conceived as a chapter on future scenarios and policy options for deserts, not the semiarid drylands. The version presented here is slightly different from the final version of the chapter submitted for publication, in that it contains only my own contributions and not those of my co-authors. However, the content of the chapter benefited greatly from discussions in two authors' meetings.

CHAPTER 2

PRESENT STUDY

Summary

The methods, results, and conclusions of this study are presented in the papers and chapters appended to this thesis. The following is a summary of the most important findings in these individual parts.

First part (Appendix A): This paper reviewed four contexts that have framed the desertification debate over three decades. A great deal of progress has been made in our understanding of climate variability and ecosystem behavior. The magnitude of variability that the Earth's climate displays is particularly pronounced in the drylands and explains why arid and semiarid ecosystems function quite differently from their more mesic counterparts. Similarly, we have learned that livelihood systems of human populations which rely on the variable resource base provided by dryland ecosystems are far more complex and resilient than was understood three decades ago. It might be possible to view this evolution in different fields of inquiry as a chain reaction, with the effects of advances in one field impacting those downstream. If this is the case, policies that affect land management in drylands would be the last to be impacted in the chain between scientific discovery and its application for human benefit. We might conclude that we have a variable, non-equilibrium world, but policies that still reflect an equilibrium mindset. What also emerged out of this review is the need for more interdisciplinary research which reflects the complexity of the problem of desertification by considering climatic, ecological and social perspectives simultaneously.

Second part (Appendix B): Land degradation, drought and desertification are linked through complex cause-and-effect relationships, which may be widely noted but only partially understood. The realization that the climatic and ecological functioning of drylands is fundamentally different from that of their more mesic counterparts has only slowly been integrated into the discussion about desertification and land degradation. Although it remains uncontested that land degradation and desertification are interrelated with both drought and human land use practices, understanding of the nature and magnitude of these relationships remains rather weak. It can be argued that the upsurge in interest in desertification following the United Nations Conference on Desertification was driven more by politics than science. The desertification issue has offered an opportunity for many dryland nations to garner international support for combating desertification. However, uncertainties about the scientific basis of our understanding of the processes involved make it difficult to define a clear course of action, paving the way to multiple interpretations and policy orientations.

Third part (Appendix C): This paper determined trends in monthly maximum NDVI (vegetation greenness) and rainfall for the period 1982 to 2003 throughout the Sahel. Overall, an increase in both variables, which were found to be highly correlated, was observed. However, this increase is not to be interpreted as an unexpected "improvement" of conditions but is merely the rising limb of interannual and –decadal rainfall variability. Whether the greening is a return to pre-drought vegetation conditions or a transition to a new equilibrium state, however, remains unknown. The spatial pattern of the observed trends is not uniform, with some areas having greened more than others. The high correlation between 3-month cumulative rainfall and vegetation greenness over time enabled us to predict greenness from rainfall fairly well using linear regression. This is not surprising, since moisture is the key constraint to vegetation growth in the Sahel region. Significant trends in time series of NDVI residuals revealed areas in where factors other than rainfall played a significant role in determining vegetation greenness. Positive trends in NDVI residuals indicate areas where vegetation has greened more than would have been expected from the increase in rainfall alone, for example in the Central Plateau of Burkina Faso. Negative trends in NDVI residuals point to areas where the greening has been less than expected from the observed increase in rainfall, for example some areas in northern Nigeria. The hypothesis that deviations in the observed NDVI from the rainfall-predicted NDVI are caused by a human factor, such as land management, seems likely for some sites (from the literature) but must be confirmed in the field for others.

Fourth part (Appendix D): This short study tested the possibility of expanding the analysis which was carried out based on coarse-scale NOAA AVHRR NDVI and GPCP rainfall data to the finer scale SPOT Végétation NDVI and RFE rainfall data. Comparison of the two coarse scale and the two finer scale datasets showed marked differences. These differences, possibly rooted in differences in data acquisition, resolution and calibration, were found to be neither spatially nor temporally consistent and make a direct transfer of the rainfall-NDVI relationship computed from one dataset to the other problematic. This inconsistency points to the need for cross-calibration between different sensors and datasets, if they are to be used in combination.

Fifth part (Appendix E): Scenarios of change for several variables relevant to desert development were analyzed: population, resource demand, climate, globalization, water, land degradation, and biodiversity. The scenario analyses show that there is a wide range of possible outcomes for deserts, or an array of alternative futures. Uncertainties arise from unanticipated political and economic changes as well as unforeseeable technological breakthroughs. The quality of their data used, incomplete understanding of the functioning of ecological, social and economic systems, and approximations and generalizations made in the scenario building process add to these uncertainties. Particularly for desert ecosystems, whose most predictable feature seems to be unpredictability, forecasts are both hard to make and inevitably fallible. Which of the possible paths of development deserts will follow depends greatly on the mindset that is behind environmental and economic policies which, directly or indirectly, concern deserts. In the face of globally increasing resource shortages, deserts hold a unique position with respect to the key resources of water and energy. Because water is in such short supply, deserts should be in the forefront in developing and testing water-efficient technologies and policies, which are likely soon to become globally relevant as water demand increases worldwide. Energy might hold another opportunity for development in deserts, because of the implications of increasing scarcity of fossil resources and the impact of their use on the global climate hold for society. More emphasis will have to be placed on renewable energy. The low cost of land and abundance of solar energy should offer deserts an advantage on which they might capitalize.

Conclusions and future directions

The studies which were assembled in this dissertation shed light on different aspects of human-environment relationships in drylands. The variability and unpredictability so characteristic of dryland environments pose particular challenges to their development. These challenges have frequently been ignored by natural resource managers and policy makers, particularly those trained in more mesic environments. Conversely, dryland environments seem less forgiving in the face of human pressure than some other environments and more likely to transition into a different state, which is expressed in a quasi-permanent change in the ecological composition of a site. Such changes have been interpreted as degradation or desertification; or as rehabilitation or improvement if the change was perceived as desired or positive. Caution is warranted however with respect to value judgments because they necessarily depend on perspective and perception of the evaluator and the "use" that is implicitly intended for a particular site.

Human and natural forcing factors which help push the system to change are very difficult to disentangle, as their effects can look very similar. Likewise, the interpretation of change as (quasi-) irreversible transition is challenging and might need to be done site by site on a strong empirical basis. To date, empirical studies which build on datasets extensive enough to evaluate causation and reversibility of observed ecosystem changes rarely exist. The third part of this dissertation (Appendix C) is an attempt to conduct such an empirical study at a regional scale for the West African Sahel. While the results are promising and point to areas in which the impact of human factors is likely to have modified the simple rainfall-vegetation connection more work needs to be done in order to understand the exact nature of this alleged impact.

To this end, it would be useful to investigate the land use histories of the areas of interest and to study village- and household-level decision making with respect to their environment. A further question which emerged from this research concerns the meaning of the observed greening in terms of vegetation composition and its evaluation by the people who rely on it for their livelihood: Does the increased vegetation imply a return to pre-drought conditions or a transition to a different ecological state? In the latter case, what – if any – are the economic implications of this change of the resource base? To answer these questions, if only for a few selected sites, would expand beyond the scope of this dissertation, but will certainly provide an incentive to the author to carry on with this research.

APPENDIX A:

THE CHANGING CONTEXTS OF THE DESERTIFICATION DEBATE

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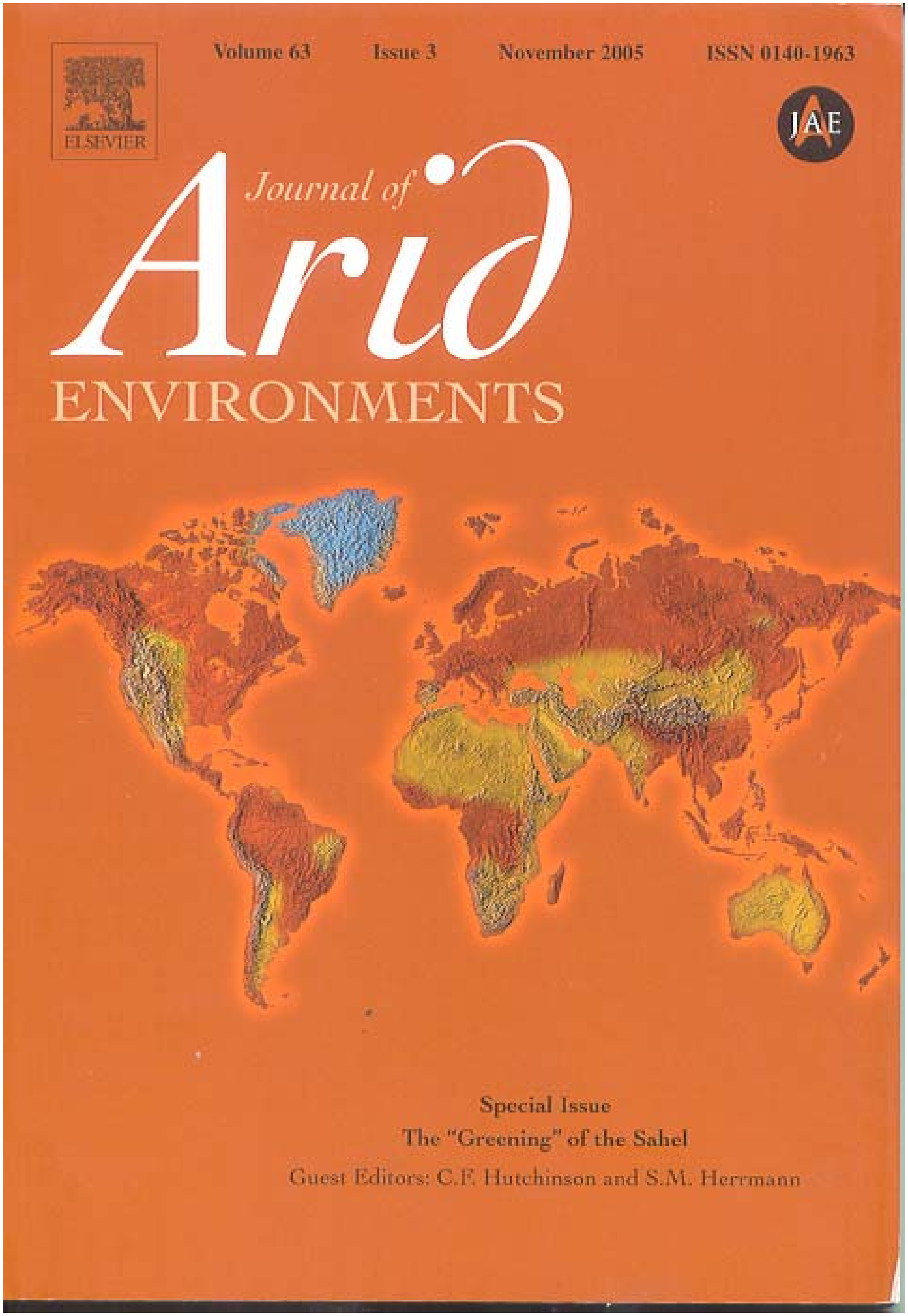
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The changing contexts of the desertification debate

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Abstract

A great many debates have grown up around the notion of desertification as a process of degradation that affects the arid, semi-arid and sub-humid zones of the globe. A fundamental and continuing debate has been over whether desertification actually exists and, if so, how it might be defined, measured and assessed. Rather than simply review the evolution of these debates we examine the contexts in which they take place and how those contexts have contributed to the evolution of our understanding of the intertwined processes that contribute to desertification. The fact that these contexts have changed over time, combined with the fact that some of them are often ignored have both helped to sustain debate. We consider four contexts that frame much of the debate and consider what impact each has had: (1) changes in our understanding of climate variability; (2) changes in our understanding of vegetation responses to perturbation; (3) changes in our understanding of social processes, including household responses to economic perturbation; and (4) changes in our understanding of desertification as a political process or artifact.

Keywords: Desertification; Paradigms; Climate; Rangeland ecology; Livelihoods approach; Environmental policy

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1. Introduction

The concept of desertification emerged during colonial rule in West Africa out of concerns about signs of desiccation and the creeping of the Sahara desert into the Sahel (e.g. Bovill, 1921; Stebbing, 1935). The actual term 'desertification' is credited to Aubreville (1949), who used it to describe the change of productive land into desert as a result of man's activity in the tropical forest zone of Africa.

Renewed attention was drawn to the desertification concept when a series of droughts began in the late 1960s that contributed to famine conditions in several Sahelian countries, and was exacerbated by political instability and unrest. The United Nations Conference on Desertification (UNCOD), held in Nairobi in 1977, was the result of an upsurge in interest in the Sahel in the aftermath of the initial round of droughts as to what measures might be taken to reclaim the areas that had been damaged. The conference not only launched the desertification issue into the political arena but also triggered a great deal of scientific interest—and controversy. A heated and ongoing desertification debate has raged after this conference, reflected in a plethora of literature and the existence of more than a hundred definitions of desertification (Glantz and Orlovsky, 1983). Blame was alternately assigned between anthropogenic and natural processes, yet there was a lingering imprecision and unclarity about the nature of the problem and a lack of measurable criteria. As a result, evaluations of the extent and rate of desertification have varied greatly. At one end of the spectrum came highly alarmist claims that 'at least one third of the present global deserts are man-made, […], the result of human misuse of the land' (UNEP, 1991) and 'desertification is a worldwide problem directly affecting 250 million people and a third of the earth's land surface' United Nations Convention to Combat Desertification (UNCCD, 2003) At the other end of the spectrum, were counter claims that there was no uniform degradation, that were drawn from selected ground data on increased agricultural production (e.g. Mortimore, 1989, 1998; Niemeijer and Mazzucato, 2002; Tiffen and Mortimore, 2002; Warren, 2002). A great deal of the criticism brought against the desertification concept refers to desertification as a 'myth' based on unsubstantiated claims, that has developed a life of its own (Thomas and Middleton, 1994). Indeed, the term desertification refuses to fade away be it in scientific or popular circles, despite its obvious imperfection and inadequacies. While habit may explain the persistence of the term in casual speech, the continued use of it in official speech requires another explanation, which needs to be approached within the larger context of the desertification debate.

Discussions about desertification have taken place against the backdrop of major developments in the fields of climate studies, ecology, social and political sciences, which nourished and helped sustain the debate. Rather than simply review the evolution of the desertification debate we examine the contexts in which this debate has taken place and how those contexts have contributed to the evolution of our understanding of the intertwined processes that contribute to desertification. We trace the development of four contexts that frame much of the debate and consider what impact and implications each of them had: (1) changes in our understanding of climate variability; (2) changes in our understanding of vegetation responses to perturbation; (3) changes in our understanding of social processes, including household responses to economic perturbation; and (4) changes in our understanding of desertification as a political process or artifact.

2. Changing understanding of climate variability

Determining the contribution of climate variability to desertification is a complex matter, and it is virtually impossible to separate the impacts of drought and desertification, because these processes often work together (Nicholson et al., 1998). Climatic perspectives on the nature and causes of the Sahelian desiccation (Hulme, 2001), the most striking example of climate variability worldwide, have been modified in past decades due to advances in climate observation, monitoring technology and mathematical modeling. Current ideas about the linkages between climate and desertification fall into two broad categories: internal feedback mechanisms, and global circulation changes related to patterns of sea-surface temperature (SST).

2.1. Internal feedback mechanisms

In the 1970s, internal forcings provided the only explanation of droughts. Biophysical feedback mechanisms between land surface and precipitation were studied by Otterman (1974) and Charney et al. (1975). Their hypotheses argued that desertification actually contributes to drought, and not vice versa.

Otterman (1974) was perhaps the first to propose the idea that modification of land cover characteristics in dryland regions might have climatic effects, citing the example of the Sinai–Negev region, where the denudation of bright sandy soil by grazing on the Egyptian side increased albedo and decreased surface temperature compared to the more densely vegetated Negev side.

Following a similar line of reasoning, Charney et al. (1975) used a global circulation model to show a positive feedback mechanism between a decrease in plant cover and corresponding decrease in precipitation via increasing albedo, radiative cooling of the air column above and thereby an enhancement of large-scale atmospheric subsidence and desiccation. In the years following the introduction of Charney's hypothesis, there has been substantial effort made to examine the sensitivity of regional rainfall to large-scale changes in land cover through climate modeling experiments, the results of which support Charney's basic hypothesis that sufficient changes in albedo can, at least potentially, produce droughts. However, satellite measurements of actual sub-Saharan albedo show no evidence for the persistent increase in albedo necessary to produce significant differences in rainfall (Folland et al., 1991; Hulme, 2001). Observed changes in albedo due to conversions of land surface characteristics have been localized in extent and often short in duration, in contrast to the widespread and sustained changes assumed in the modeling studies. On another note, a decrease in vegetation density does not necessarily lead to an increase in albedo, but can in certain cases decrease albedo by reducing the number of geometric elements that reflect incoming solar radiation (Ba et al., 2001). Despite the absence of supporting empirical evidence for the Charney hypothesis, modeling studies are valuable as simulation experiments for understanding the inter-relationships between land surface and atmospheric processes (Hulme and Kelly, 1993).

More recently, Balling (1991) put forward a contrasting but not widely supported hypothesis that desertification produces a warming trend at regional scales, which could be mistaken for a signal of greenhouse warming. Subsequent studies did not support this idea because in the Sahel region, where desertification is most prevalent, the warming trend has actually been smallest of all dryland regions, possibly due to the increased atmospheric dust loading resulting again from human-induced land cover changes (Hulme, 1996).

The role of dust in affecting precipitation is equally controversial. Contrary to what some theoretical models predict (Yin et al., 2000), Rosenfeld et al. (2001) suggest that mineral dust in the atmosphere actually reduces precipitation efficiency of clouds due to the coalescence-suppressing effects of large concentrations of dust particles. In addition, dust can inhibit the formation of convective clouds because of radiative cooling and increased subsidence. That would mean that higher dust frequency might be the cause rather than the result of the decreased rainfall. Thus, we find that dust emissions from anthropogenic sources can provide a mechanism for initiating a desertification feedback cycle (Rosenfeld et al., 2001). On the other hand, the dust loading over the Sahel has clearly followed, rather than preceded, the trends in precipitation (Nicholson et al., 1998).

The impact of dust on warming is a complex issue, because it modifies both the incoming shortwave solar radiation and outgoing longwave radiation, either a cooling or heating effect can occur, depending on cloud cover and the albedo of the underlying surface (Nicholson, 2001).

2.2. *External forcings*

With improved capabilities for monitoring global phenomena (i.e. satellite remote sensing), emphasis has shifted to characterizing and understanding external forcings as possible explanations for drought. Satellite data also showed that most environmental variability in the Sahel (i.e. vegetation greenness) is directly related to rainfall (Tucker et al., 1991; Tucker and Nicholson, 1999).

Based on extensive instrumental records of precipitation as well as satellite-derived precipitation estimates, Nicholson (2001) argued that rainfall anomaly patterns in Africa tend to be continental in scale. However, she found that West Africa stands out from the rest of the continent through a pronounced year-to-year persistence of anomalous conditions. While earlier explanations of the causes of Sahelian drought focused on anomalies in the latitudinal displacement of the ITCZ, now large-scale changes in SST patterns are felt to be the major driving forces that promote changes in atmospheric circulations. The influence of the El-Nino Southern-Oscillation phenomenon has been discussed, but so far without consensus of the scope of its influence.

During dry years in the Sahel, SSTs tend to display a pattern of negative anomalies north of the equator and simultaneously positive anomalies south of the equator (Folland et al., 1986, 1991). This pattern of SST anomalies seems to induce changes in the atmospheric processes over West Africa: the African Easterly Jet (AEJ) is stronger under these conditions than in average years and displaced equatorward, while the Tropical Easterly Jet is weaker than in average years. These findings are seen as strong evidence for a relationship between large-scale oceanic and atmospheric processes (Nicholson, 2001). Simulation experiments tended to confirm the primary importance of ocean temperature forcings in climate variability of the Sahel region, modified by effects of land surface moisture feedbacks (Hulme and Kelly, 1993; Giannini et al., 2003).

While the 1980s patterns of SST were interpreted as just another result of the same atmospheric circulation processes that affected Sahelian rainfall, they are now thought of as a cause rather than an effect of the shift in atmospheric circulation that affects Sahelian rainfall (Hulme and Kelly, 1993). With the SST's influence on precipitation over West Africa now widely accepted, the question arises as to what might be the initial cause of the contrast of relatively low ocean temperatures north of the equator and relatively high ocean temperatures south of the equator. It might be caused by natural climate variability or linked to human-induced global warming.

Predicting regional responses to global warming is not simple: model simulations suggest increased rainfall for most areas, but a decrease in rainfall for the Sahel, northern Africa and the Mediterranean. Not only can global warming contribute to desertification, but desertification can also contribute to global warming by playing a role in altering sources and sinks of greenhouse gases. However, the contribution of dryland degradation to global warming is unlikely to be more than a few percent of the total greenhouse forcing (Hulme and Kelly, 1993).

Continued research and improved monitoring capabilities have led to greater insight into the complexities of the inter-relationships among climate, drought and desertification. Many initial concepts have been found too simplistic to explain the occurrence of droughts in the Sahel. Not only are the interactions between surface and atmosphere much more complex than initially assumed, they are now thought to have a less important role in influencing Sahelian rainfall than global climate forcings. In particular, the link between lower rainfall in the Sahel and a particular pattern of SST anomalies in the oceans has been well established and helps to explain the multi-decadal patterns of Sahelian climate variability, which could not be explained by local forcings alone. However, the root causes of this pattern are still unresolved.

Although the variability of rainfall has been recognized as an important characteristic of Sahelian climate and drought as a 'normal' phenomenon (Glantz, 1987), the magnitude and duration of the drought events that began in the 1960s have been unprecedented in the 20th century, and it is unclear whether this event is unique in the longer record of the Holocene. There is a great temptation to attribute this long-lasting desiccation to human interventions, but it might be argued just as easily that the wet decades of the 1920s, 30s and 50s were the anomaly rather than the following run of dry decades (Hulme, 2001).

Although a new understanding of climate variability has emerged, the understanding of the causes of this variability is still unfolding. Most probably, there is no single valid explanation, nor are the two prevalent paradigms (internal and external forcings) mutually exclusive. Relative contributions of climate variability and human agency to desertification will likely depend on specific regional contexts. The challenge remains in identifying the most appropriate explanation for any given situation.

2.3. Implications

The choice between alternative explanations of desertification carries significantly different implications for dealing with the problem. If the first mechanism (i.e. internal feedback) is judged to be the cause, there is an implicit assumption that removal of the perturbing factor (e.g. overgrazing by livestock) will allow a return to the previous condition. That is, removal of animals allows a regeneration of vegetation cover, reduces albedo, increases surface temperatures and creates conditions favorable to increased convective precipitation. If the second mechanism (i.e. external forcings) is embraced, there is little that can be done to affect the occurrence of drought. If that is the case, then the livelihood systems on which human populations depend must be made to adapt to that uncertainty: seize opportunities as they occur and endure inevitable drought.

3. Changing paradigms in rangeland ecology

Rangeland ecologists have been confronted with comparable puzzles and have arrived at a similar point through an entirely different process. New thinking in ecology has fostered a debate about the validity of the two competing paradigms of vegetation dynamics in rangelands: is rangeland ecology a system based on equilibrium or non-equilibrium? The current understanding of the ecological functioning of arid and semi-arid rangelands, although largely theoretical so far, has implications for current interpretation of land degradation and desertification that parallel those of the current interpretation of the climate context.

3.1. Equilibrium models

Until the 1970s, it can be argued that the equilibrium paradigm prevailed in much ecological thinking and, perhaps more importantly, guided most land management policy. The equilibrium paradigm holds that internal ecosystem regulation is achieved through negative feedback mechanisms that move the system toward stability. The metaphor that most aptly describes it might be the 'balance of nature' (Briske et al., 2003). The ecological model associated with the equilibrium paradigm is 'succession' which was developed to explain vegetation dynamics in North America (Clements, 1916). It argues that there is a 'climax' vegetation for each particular site that is determined by climate and soil. In this model, when the climax is perturbed (i.e. changes in use; variability in climate), vegetation is pushed back in the successional sequence to a sub-climax (Behnke and Scoones, 1993). Within this model, vegetation of a particular site at a particular time is viewed as point along a linear trajectory from poor (or very disturbed) to excellent (or climax) (Dyksterhuis, 1949). The succession model provided an easily understood planning and management tool for rangelands, with a management objective that could be achieved through the adoption of an equilibrium grazing policy. This model might still be applicable for some systems, particularly those with less variable climate, but its adequacy to describe vegetation dynamics in highly variable arid and semi-arid environments has been challenged (Westoby et al., 1989; Behnke and Scoones, 1993; Sullivan and Rohde, 2002).

3.2. Non-equilibrium models

Challenges to the equilibrium model argue that arid and semi-arid environments must necessarily function as non-equilibrium systems that are more dynamic and less predictable than equilibrium systems as a function of inherently variable climate. The metaphor for the non-equilibrium paradigm is the 'flux of nature', referring to its limited capacity for internal regulation and greater potential for transit among multiple equilibrium points (Briske et al., 2003). The non-equilibrium paradigm describes event-driven vegetation dynamics that are driven by periodic and stochastic climatic events, which result in discontinuous and possibly non-reversable changes. One version of the non-equilibrium paradigm is the 'threshold' model (Holling, 1973). This model holds that there are thresholds that, once crossed, offer entry into a number of other possible states. These states can be distinguished on the basis of community physiognomy, plant growth forms or soil properties. Thresholds suggest that changes are irreversible, even after removal of the disturbance causing the change. The findings of Schlesinger et al. (1990) from the Jornada Experimental Range in southern New Mexico support the hypothesis of irreversible thresholds. There, increasing heterogeneity of the soil resources triggered a positive feedback mechanism that reinforced the establishment of a new functional state of the ecosystem via changes in physical properties (i.e. soil texture and surface temperature) and biogeochemical cycles (i.e. availability of water and nutrients).

The 'state and transition' model (Westoby et al., 1989) merged, in a sense, the succession and threshold models. It holds that while systems may cross thresholds when disturbed (transition), they then enter into any one of a number of alternative equilibria (states). It allows for succession, but also discontinuous and irreversible transitions between alternative stable states, which may occur quickly or over an extended period of time. The challenge of the state and transition model consists in defining a catalogue of states and transitions, depending on context and management objective.

Ellis and Swift (1988), on the other hand, assumed persistent non-equilibrium conditions in arid systems, which lead to a complete de-coupling of herbivores and vegetation in a sense that both herbivore numbers and vegetation condition are so strongly controlled by climatic variability that interactions among them are negligible in comparison. This is consistent with the 'autecological hypothesis' of system regulation in arid environments, according to which the responses of individual species to stress play a greater role in structuring the ecosystem than interactions among species (Noy-Meir, 1973).

The limited availability of data on long-term vegetation dynamics limits the evaluation of alternative paradigms and models. Currently, empirical evidence on species replacement through time after exclusion of grazing and existence of event-driven vegetation dynamics are used to distinguish between equilibrium and non-equilibrium patterns. However, exclusive emphasis on vegetation might be insufficient for evaluation, since species fluctuations could be a compensatory mechanism actually contributing to ecosystem stability (Schlesinger et al., 1990; Briske et al., 2003). Moreover, equilibrium and non-equilibrium dynamics are not mutually exclusive, but represent two ends of a continuum within which most systems fall (Wiens, 1984). Depending on spatial and temporal scales, most systems exhibit both equilibrium and non-equilibrium characteristics, particularly in semi-arid regions (Illius and O'Connor, 1999). Shifts between equilibrium and non-equilibrium dynamics have also been observed over time. Briske et al. (2003) argue that the appropriate question is not whether equilibrium or non-equilibrium dynamics apply, but which dynamic applies within a given situation.

3.3. Implications

This new understanding of ecosystem dynamics undermines the model around which most land management policies are built. One is the realization that the number of animals that might be sustained on arid and semi-arid rangelands is not static: it must necessarily vary as a function of climate. This, perhaps, is not surprising even to those who would embrace an equilibrium model. The more important consideration is that failure to accommodate variability may lead to a fundamental change in the ecosystem. Managing rangelands on the basis of a non-equilibrium understanding is a game of calculating probabilities 'the object of which is to seize opportunities and to evade hazards' (Westoby et al., 1989, p. 266).

4. Changes in our understanding of socio-economic processes

In addition to climatic and biophysical variables, the relationships that people have with their land—the land use and land management strategies employed by individuals, households and communities—are important components of the managed dryland ecosystem that effect processes of land degradation and land rehabilitation (Blaikie and Brookfield, 1987). As with the equilibrium model in ecology, an equilibrium understanding of rural livelihoods and land use systems prevailed for much of the past century. According to equilibrium thinking, 'rational' land use practices were assumed to be well-established and stable adaptations to an environment that sought equilibrium (e.g. Luker, 1956). Thus, when signs of environmental decline became obvious in the Sahel in the aftermath of the great droughts, they were interpreted as indicators of mismanagement and overuse of resources by peasant farmers and livestock herders. Inspired by the findings of the UNCOD in 1977, scientists and government officials portrayed the people of the Sahel as responsible for the degradation of their own environment, some going so far as to blaming West Africans for causing or at least exacerbating their own droughts (e.g. Charney et al., 1975; WCED, 1987; Leonard, 1989). Opportunistic strategies employed by land users, such as herding methods based on constant migration and fluctuating herd sizes, were misunderstood by Western scientists and condemned as being environmentally damaging. As a result, efforts were made to remedy these land use practices through counter-productive prescriptions of conservative stocking strategies based on calculated carrying capacities, which undermined the very strengths of the indigenous land use systems (De Leeuw and Tothill, 1990; Bartels et al., 1993). Contrary to the views of colonial and post-colonial scientists, as a result of their long and intimate contract with their environment, most indigenous people have developed strategies to cope with uncertainties which make economic and ecological sense (see, e.g. Mortimore, 1989; Scoones, 1994), and, unless droughts hit with unusual severity, these strategies help to sustain rather than destroy their resource base (Broad, 1994). This is not to say, though, that economic hardship and some pockets of land degradation do not exist, at least periodically.

The failure of western-trained scientists to come to a functional understanding of the rationales of indigenous livestock herders and peasant farmers can be traced to failures in communication between the two groups and the erratic nature of the visits of scientists to rural sites could not lead to a deeper insight into site-specific social contexts (Mortimore, 1989; Fairhead and Leach, 1996). In contrast, Mortimore's studies (1989, 1998) benefited from his long involvement with villagers in Northern Nigeria, which spanned the worst drought in a century. Through interviews, time spent with families, and direct observation, he found remarkably resilient, though not stable, survival systems in the Sahel and well thought-out, rational responses to the drought crisis. During drought, farmers shifted to other crops, intensified weeding operations, diversified their sources of income to production of goods, and temporarily out-migrated—a flexibility in adaptation that has been present in African farming systems from time immemorial, especially in drought-prone areas. These adaptation strategies have not been static, instead they have responded to changing environmental and economic conditions as well as population pressure. In addition to the evolution of livelihood strategies, new local knowledge is continuously and actively created through agricultural experimentation (see, e.g. Reij and Waters-Bayer, 2001).

Apart from agricultural experimentation and innovation, new, and widely overlooked, developments have been taking place outside the agricultural sector. Since colonial times, the economic future of Africa was viewed almost exclusively in agricultural terms, be it in the form of a large-scale 'modern' agriculture (plantations, estates, commercial farms and ranches) or the small farm model (Ellis and Biggs, 2001). However, African rural populations have engaged in widespread rural income diversification that does not revolve around agriculture, with many societies undergoing a process of 'de-agrarianization', challenging economic theories about the role of agriculture in growth and poverty reduction (Bryceson, 2002). Estimates from different sources indicate a surge in non-agricultural income during the past 15 years to about 40–60% of the average rural household income which, paradoxically, appears to have been triggered by structural adjustment programs originally designed to support peasant farming (Ashley and Maxwell, 2001; Bryceson, 2002). This development of income diversification—inside and outside the agricultural sector—is also captured in the literature of the livelihoods approach (see, e.g. Carney, 1998; Scoones, 1998; Ellis, 2000; Ellis and Biggs, 2001), the origins of which can be traced back to the food security literature of the 1980s (Sen, 1981; Swift, 1989).

4.1. Livelihoods approach

A growing body of literature gives evidence of the dominance of the livelihood approach in the debate on rural poverty reduction during the last decade. The livelihood approach is an economic framework for examining rural livelihoods, which are seen to comprise 'the assets [...], the activities [...], and the access to these [...] that together determine the living gained by the individual or household' (Ellis, 2000, p. 10). Assets are expressed as sets of different capitals (natural, physical, financial, human and social), to which individuals and households have access and from which they construct their livelihood strategies. Examples of the dynamics of capital assets can be found in case studies from Southern Africa by Twyman et al. (2004). Tiffen et al. (1994) identify three broad clusters of livelihood strategies: (1) agricultural intensification or extensification; (2) livelihood diversification; and (3) migration. The combination of livelihood strategies has an influence not only on the livelihood security of the household, but also on the environment. The relationship between livelihoods and the environment has been examined by many authors (e.g. Blaikie and Brookfield, 1987; Mortimore and Adams, 1999). While many earlier works assume a self-accelerating downward spiral between poverty and natural resource depletion, with population growth as a critical factor (Leonard, 1989), this view has been questioned by a number of case studies which point out evidence of poor rural people actively improving their environments using labor-intensive conservation practices (Tiffen et al., 1994; Mortimore, 1998; Tiffen and Mortimore, 2002). Although farmers generally avoid land use practices that jeopardize their yields in the long run, increased livelihood stress due to labor shortage or a collapse of market prices for cash crops may cause temporary neglect of conservation practices. Another reason for a lack in motivation to routinely carry out conservation practices is insecurity of land tenure (Ellis, 2000).

Access to assets is an important determinant—as expressed earlier in Sen's (1981) work by the concepts of endowment and entitlement—and was found to differ greatly among households, depending on their place in society and institutional rules. As a consequence, coping strategies in the face of environmental and other stresses also differ considerably among households (Vogel and Smith, 2002). The coping strategies available to a household depend highly on the level of livelihood diversification the household has reached, with better-off households typically able to diversify in more favorable labor markets with higher returns than poorer households, which have higher entry barriers into lucrative labor markets. Diversification contributes positively to livelihood sustainability—a widely used concept that relates to economic well-being as well as to the environment—because it helps to reduce the vulnerability to shocks and stress. In terms of environmental degradation, however, Warren (2002), who has introduced the notion of 'land degradation is contextual' and points out that the fields worked by households with many options were found to be more affected by erosion than those of households with fewer options.

The antithesis of livelihood sustainability, livelihood insecurity, is dealt with by Devereux (2001), who distinguishes between risk management and coping strategies in dealing with environmental and economic insecurities. Whereas the exposure to risk is generic and affects large populations, the susceptibility to actually experience adverse consequences is specific to individuals and individual households and depends very much on risk management and coping strategies, which in turn are determined by a household's economic and social standing and the existence of community support systems. With ex ante risk management strategies, such as spreading risk by diversifying livelihoods, preferable to ex post coping strategies, he advocates pro-active interventions in the form of publicly provided social protection programs, many of which were dismissed in the 1980s as market-distorting (Devereux, 2001).

4.2. Implications

The implications of the renewed understanding of socio-economic processes and indigenous land management practices within the context of the desertification debate are two-fold. First, rather than understanding them as ignorant or irrational, the recognition of the rationale and adaptive capacity of indigenous land management practices requires that these practices be incorporated into development and environmental schemes to strengthen rather than remedy them. This would imply the adoption of more democratic forms of interaction and cooperation between land users on the one side and donor agencies and national institutions, which set up large-scale 'anti-desertification measures' on the other.

Second, the realization that the creation of viable rural livelihoods no longer depends solely on agricultural activities calls for a revision of policies that were exclusively aimed at extending and modernizing peasant production in favor of policies supportive of occupational diversification and specialization in all sectors of the rural economy. Policies are needed that facilitate access to a wide range of assets to foster the construction of resilient and environmentally sustainable livelihoods. However, because as livelihoods are diversified, so too are their potential impacts on the environment.

5. Changing understanding of political dimensions

A discussion of desertification at any scale must also take into consideration the institutional and political settings of the problem which define the framework in which decisions by individual households are made and executed (Batterbury et al., 2002). The political dimension encompasses national economies, administration and law as well as international institutions, organizations and regimes (public and private, government and non-government). Each of these can either offer opportunities or pose constraints to the construction of local livelihoods in the face of land degradation, thereby linking local vulnerability to national and international processes and regimes (Downing and Lüdeke, 2002). Like individual households, national societies differ in their capacity to cope with the impacts of land degradation on their biophysical environment, which induces further context-dependency of the land degradation problem (Warren, 2002).

Another dynamism has been introduced into the desertification debate by inevitable political developments in the Sahel region and the world on the one hand (i.e. incorporation of the Sahel into regional and global institutions, changes in governments, and a tendency toward decentralization) (Batterbury and Warren, 2001), and changes in development paradigms (i.e. continuing evolution of scientific and political thinking on the nature of development) (Peet and Hartwick, 1999; Berger, 2004; Randall, 2004).

The role of politics and institutions in the 'creation' of desertification (Batterbury et al., 2002) has brought up a debate between advocates of different environmental and developmental discourses, which Adger et al. (2001) broadly divided into two camps: the Global Environmental Management discourse and the populist discourse. While both discourses agree on the existence of global environmental problems, they are embedded in two polarized perspectives on development. The Global Environmental Management discourse has its philosophical roots in both modernization/stages-of-economic-development theories (Rostow, 1960) and neo-Malthusian thinking. In contrast, the populist discourse has been influenced by Marxist and neo-Marxist theories and draws upon ideas from the dependency school of development (e.g. Dos Santos, 1970; Prebisch, 1971; Cardoso and Faletto, 1979; and, for the Sahel, Franke and Chasin, 1980) and their post-structural and post-developmental critiques (e.g. Escobar, 1995, 2004).

Adger et al. (2001) analyses these two dominant discourses in terms of their message, their actors, and the consequent policy implications. According to the Global Environmental Management discourse, overpopulation in drylands is depicted as the main problem. Local land users and farmers are seen as both the principal causal agents and also the victims of desertification, as depicted in vicious cycles of poverty and environmental degradation. Based on a technocentric worldview and development optimism, scientists, aid bureaucrats and national civil servants are portrayed as heroes, who enable economic take-off and provide solutions to environmental problems. By contrast, the populist discourse ('populist' referring to the positive portrayal of acts of local people and negative portrayal of foreign interventions), can be traced to the self-reliance advocacy of the dependency schools of development and has a different cast of actors. Global capitalism, transnational corporations and northern consumers are the villains, whose interventions are to blame for a marginalization of smallholders and pastoralists which in turn leads to land degradation and exploitation. Local smallholders and pastoralists are simultaneously victims and heroes (Adger et al., 2001).

Both discourses have had considerable political impact and also scientific impact on the desertification debate. While the Global Environmental Management discourse dominates in terms of influence on environmental policies, the populist discourse also supplies important inputs. The dominance and longevity of the Global Environmental Management discourse explains, and has been explained by, the institutionalization of the desertification debate (Thomas and Middleton, 1994), starting with the UNCOD, held in Nairobi in 1977 in the aftermath of prolonged droughts and famine in the Sahel. The conference resulted in the creation of a Plan of Action to Combat Desertification (PACD), to be coordinated by the UNEP and implemented by governments at the national scale (Batterbury et al., 2002). The institutionalization of the desertification debate received another boost at the United Nations Conference on Environment and Development (UNCED) in 1992, when the magnitude and global character of the issue was found to require the elaboration of an international environmental convention, the UNCCD. Though being a global level regulatory framework, the UNCCD is based—at least nominally—on the principles of participation and decentralization (Adger et al., 2001) and thus reflects the change in development thinking which has taken place since the UNCOD.

The dominance of the GEM discourse in terms of influence on environmental policies has been reinforced by both cultural and economic globalization processes and scientific advances in detecting global-scale environmental problems (Adger et al., 2001). Until recently, the assumptions that national and international top-down regulations would be the solution to 'unsustainable' resource management and the land degradation that accompanied it was almost unquestioned and thus enjoyed widespread support in governments and international institutions (Mortimore and Adams, 2001). Despite the poor success rate of top-down schemes in mitigating symptoms of desertification that were marked by failures of interventions in terms of biophysical and social sustainability (Batterbury et al., 2002), the 'official' discourse on desertification in many places continues to justify land policies based on increasing central control and regulation. While portraying rural resource users as 'incapable resource stewards', many African governments claim stewardship over resources in the name of 'sustainable development' and 'combating desertification' (Vogel and Smith, 2002). Sullivan (2000) cites the example of north-west Namibia, where claims of widespread desertification form the basis for a severely repressive policy, despite the lack of evidence of desertification actually occurring.

Recently, however, in the face of obvious failures of past top-down schemes, decentralization policies and bottom-up planning methods and participatory approaches—in accordance with ideas from the populist discourse—are slowly being adopted in most dryland African countries (Batterbury et al., 2002). Opinion on the effectiveness of decentralized management solutions is still divided, because commercial interests and indigenous knowledge compete with each other to create sustainable land use. Moreover, bottom-up approaches are more difficult to reconcile with the terms of bilateral and multilateral funding than their top-down counterparts (Downing and Lüdeke, 2002). Lastly, the reluctance to adopt novel approaches and the willingness to embrace the GEM discourse despite its obvious inadequacies can be explained by the fact that the latter was created by and convenient for the interests of three main groups of actors (its 'heroes'): colonial and national governments, international aid donors, and scientists (Thomas and Middleton, 1994; Swift, 1996; Adger et al., 2001). The complex interactions among a range of actors in the making of environmental policy is highlighted by Keeley and Scoones (2003) through a number of case studies on land management and soil fertility.

UNCOD and its subsequent institutionalization have also boosted scientific interest in desertification and funding opportunities for research. Research findings, however, have not always had an impact on poor people's livelihoods, nor have they translated into appropriate policies or development interventions. Under the dominant GEM discourse, research had followed the conventional unidirectional mode, with little opportunity for external inputs into the research domain. With the introduction of participatory approaches to development, the research process has taken a more interactive shape, with more dialogue between land users and implementers of desertification research (Batterbury et al., 2002). This 'democratization' of the research process is paralleled by a rise in interdisciplinary research methods that break down of the dualism between natural and social sciences (Batterbury and Bebbington, 1999; Scoones, 1999).

5.1. Implications

The GEM discourse and the populist discourse suggest alternative explanations of the desertification problem and therefore imply different strategies for mitigating it. Following the GEM discourse, technocratic interventions by external actors would be seen as the appropriate solution for environmental problems perceived as rooted in poverty, underdevelopment and population pressure. At the other end of the spectrum, embracing the reasoning of the populist discourse would mean abandoning external interventions, which are part of the problem, and empowering local communities, which are better off when left to their own devices.

In reality, however, policy implications of the two theoretical discourses are rarely found in their pure form, as they largely overlap and refine each other through an ongoing dialectic. The World Bank and IMF, themselves products of GEM thinking, have taken over elements of the populist discourse. Their structural adjustment programs now encourage more community participation, drive decentralization initiatives and recognize common property institutions. Despite the validity of the populist discourse and other dissenting voices, desertification policies are still biased toward the GEM discourse, which has been sustained through the institutionalization of the desertification debate and exported via donor-funded projects.

6. Conclusions

Since 1977, the four contexts considered here that frame the desertification debate have evolved considerably. It would be easy to claim some superior position in the debate that is afforded us simply by the passage of time and the accumulation of the wisdom that has been generated during the intervening period. As is demonstrated here, it is true that a great deal of progress has been made in our understanding of climate variability, and ecosystem function. Perhaps the most significant advance has been our emerging understanding of the magnitude of variability that the Earth's climate displays, perhaps nowhere more profoundly than the semi-arid parts of the globe. Not surprisingly, contemporaneous models that attempted to describe ecosystems and how they responded to perturbations (both 'natural' and human-induced) also evolved: inconstant climate combined with observed failings of the 'succession' model of vegetation response doomed the universal appeal of the notion of natural systems tending inevitably to climate-defined 'equilibrium'. Similarly, we have learned that, to varying degree, the livelihood systems of human populations which rely on these chaotic resources are far more complex and resilient than was understood more than a quarter century ago. It might be possible to view this evolution in disparate fields of inquiry as something like a chain-reaction, with the effects of advances in one field affecting those down-stream. If this is in fact the case, then we might argue that it is not surprising that policies that affect land management in arid and semi-arid regions would be the last to be effected in the chain between scientific discovery and human benefit. In many ways, we might conclude that we have a non-equilibrium world that is saddled with an overriding equilibrium mindset and policies that reflect it.

What also emerged out of this review that was already emphasized by Scoones (1999) and Batterbury et al. (2002), is the need for research in each of these broad disciplinary areas to proceed in parallel rather than series. In other words, research that relates to development should, by necessity, be interdisciplinary in order to take in the ecological and social complexity inherent in drylands. Discussion of desertification from the social science perspective still tends to base its understanding of the dryland environment on outdated ecological models; ecologically motivated assessments of desertification, on the other hand, often fail to incorporate new insights from the social sciences; and, finally, because they may be driven by perverse or parochial interests, policies that affect people on the ground may be formulated largely independent of science that is current and thus may serve to degrade rather than enhance the lives of people most affected.

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APPENDIX B:

THE SCIENTIFIC BASIS: LINKAGES BETWEEN LAND DEGRADATION, DROUGHT AND DESERTIFICATION

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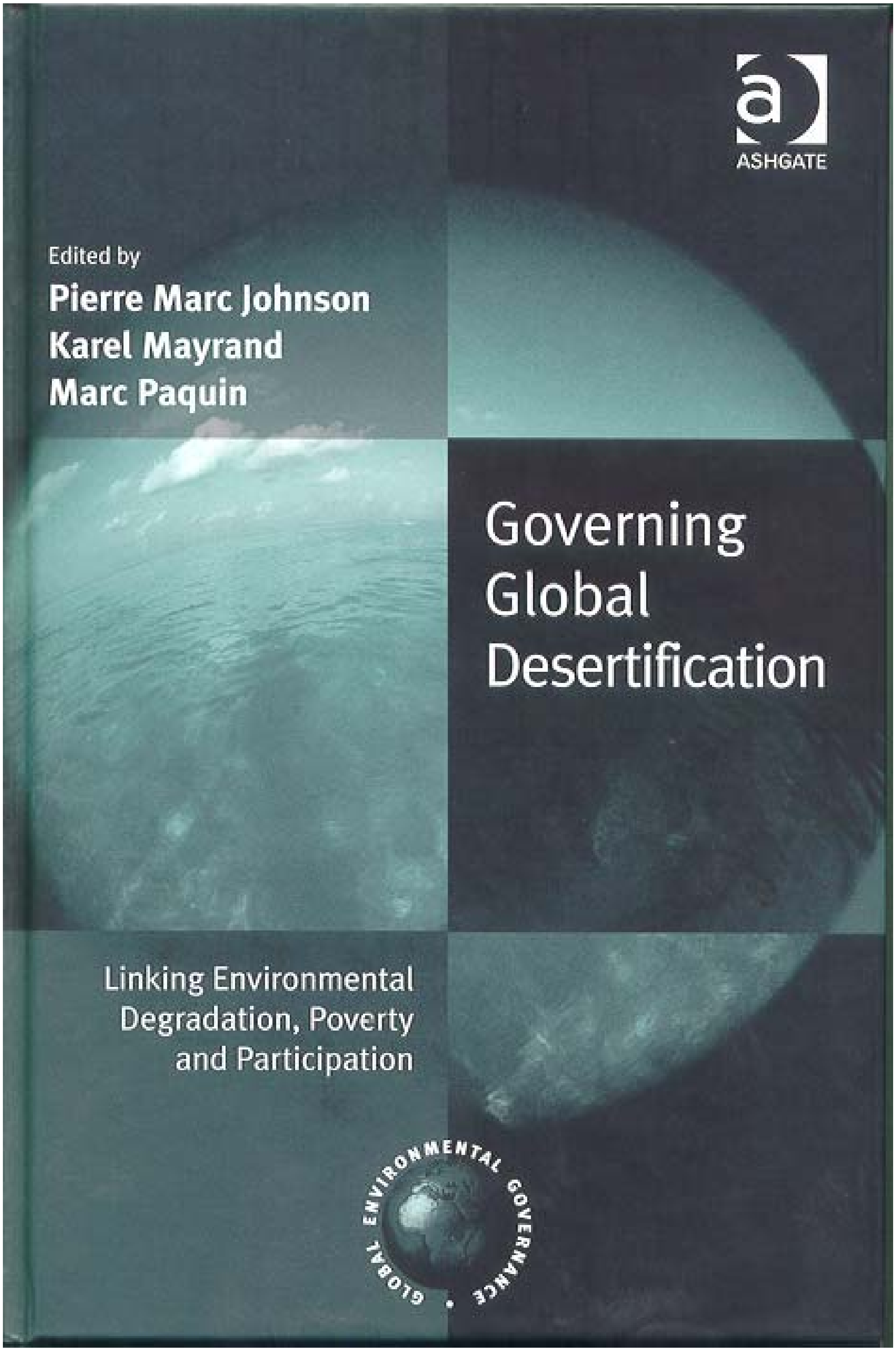
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Governing Global Desertification
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Chapter 1

The Scientific Basis: Linkages Between Land Degradation, Drought and Desertification

Stefanie M. Herrmann and Charles F. Hutchinson

Introduction

Land degradation, drought and desertification have emerged as major problems affecting dryland environments. Their alleged causes, interrelationships and implications have fuelled a great deal of controversy among scientists, land managers and policy makers. While concerns about desiccation and environmental deterioration in the world's drylands date back to colonial times in West Africa and the massive soil erosion during the 1930s that became known as the "Dust Bowl" in the American Great Plains, more systematic scientific inquiry into dryland environments only began with the establishment of the UNESCO Arid Zone Research Programme in 1951. That makes dryland research a relatively young field in science and a frontier of knowledge.

Interest in drylands, however, is vital to a range of countries, notably those on the fringe of the Sahara desert, which are classified –wholly or in large part – as arid and semi-arid. The economic future of these countries, most of which are judged to be 'developing countries', depends on the adaptation of their development strategies to the stresses imposed by their arid environments. Moreover, they are home to a significant, and rapidly growing, portion of the world population: estimates range from some 15 per cent[1] to nearly 40 per cent[2], depending on the definition of drylands and demographic data used.

The large populations affected by an unusually long series of drought years which hit the African Sahel region from the late 1960s well into the 1980s, and the human suffering it caused, brought a worldwide upsurge in scientific research on drylands, which culminated in the United Nations Conference on Desertification (UNCOD), held in Nairobi in 1977. Although much research since then has been aimed at

[1] Clarke, J. and Noin, D. (Eds.) (1998) Population and Environment in Arid Regions, UNESCO, Paris.
[2] White, R. P. and Nackoney, J. (2003) Drylands, people, and ecosystem goods and services: web-based geospatial analysis. World Resources Institute.

understanding the mechanisms behind 'desertification' and its linkages with drought and human land use, the scientific basis for recognition of desertification as an irreversible process remains rather weak. While the occurrence and severity of local-scale land degradation in many drylands is not disputed, there is insufficient scientific evidence of large-scale permanent desertification[3]. For lack of a more precise concept, however, the term desertification is still widely used in scientific or popular circles to refer to a multitude of land cover change phenomena, despite its acknowledged limitations and lack of clarity about the fundamental nature of the problem and the lack of measurable criteria.

Physical Characteristics of Drylands

Drylands are regions which are affected routinely by moisture deficits, These regions are marked not only by low precipitation totals, but also by extreme interannual variability and extended drought. While water availability is the key to understanding dryland environments, absolute amounts of precipitation tell little about dynamic processes operating in any particular region. Different disciplines involved in the study of drylands also rely on different indicators to define them (e.g. botanic and climatic). Therefore, finding an unambiguous and commonly agreed on definition and classification of drylands is hard to achieve.[4]

The work of Meigs[5], commissioned by UNESCO, still forms the basis of most definitions of arid conditions to date. He used a moisture index which relates precipitation, the main input of water into an ecosystem, to evapotranspiration, its main output, to map the distribution of arid lands worldwide (fig.1). According to the index, drylands are those areas in which potential evaporative demand exceeds total rainfall.

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[3] See e.g. Prince, S. D., Brown de Colstoun, E. and Kravitz, L.L. (1998) Evidence from rain-use efficiencies does not indicate extensive Sahelian desertification. Global Change Biology 4, 359-374.; Tucker, C. J. and Nicholson, S. E. (1999) Variations in the Size of the Sahara Desert from 1980 to 1997. Ambio 28, 587-591.; Eklundh, L. and Olsson, L. (2003) Vegetation index trends for the African Sahel 1982–1999. Geophysical Research Letters 30, 13-1 - 13-4.

[4] Beaumont, P. (1993) Drylands - environmental management and development, Routledge, London.

[5] Meigs, P. (1953) World distribution of arid and semiarid homoclimates. Review of research on arid zone hydrology, UNESCO, Paris, maps.

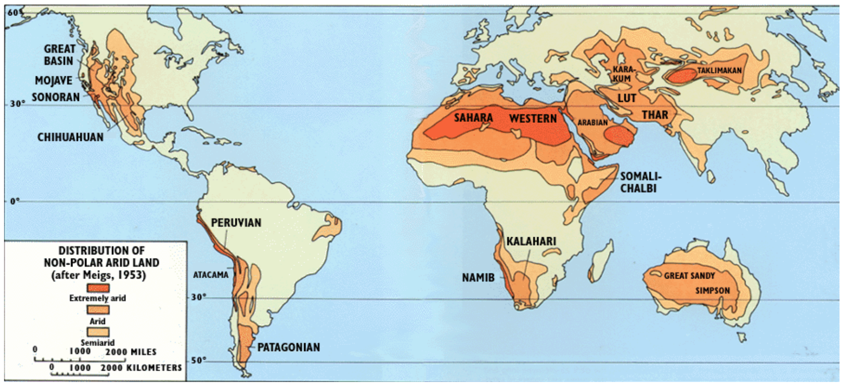

Fig. 1.1 World distribution of non-polar arid lands[6]

Geographically, the world's drylands are found (1) beneath the belt of subtropical atmospheric high pressure zones marked by the Tropics of Cancer and Capricorn (trade wind deserts), (2) in interior drainage basins of the mid-latitudes (continental deserts), (3) on the lee sides of mountain ranges (rain shadow deserts) and (4) on the western edges of continents affected by cold ocean currents (coastal deserts)[7]. They occupy approximately one third of the world's land surface and include a whole range of conditions from extremely arid to semi-arid.

While causes of aridity are complex and differ from one region to another, all of these drylands share the experience of recurring drought and thus fluctuating productivity of the resource base although these vary in their extents and implications. As extremely arid regions can support so few people, the more serious problems of land degradation are generally reported from the semiarid where the effects of drought are more profound due to a higher concentration of population[8].

Ecologically, arid and semi-arid environments, unlike their more humid counterparts, function primarily as non-equilibrium systems. Equilibrium systems are associated with the concepts of 'succession' and 'climax vegetation'[9] and served as the ecological paradigm for much of the twentieth century. In contrast, non-equilibrium systems are governed by variability and unpredictability and have offered an alternative to equilibrium models for the past quarter century. Non-equilibrium systems possess a limited capacity for internal regulation and greater potential for transit among multiple

[6] Source: USGS: http://pubs.usgs.gov/gip/deserts/what/world.html last updated: 10/29/1997.
[7] Mainguet, M. (1999) Aridity: droughts and human development, Springer, Berlin.
[8] Dregne, H. E. (1983) Desertification of arid lands, Harwood Academic Publishers, New York.
[9] Clements, F.E., 1916. Plant Succession; an Analysis of the Development of Vegetation. Carnegie Institution, Washington.; Dyksterhuis, E. J. (1949) Condition and Management of Range Land Based on Quantitative Ecology. Journal of Range Management 2, 104-115.

equilibrium points[10]. Vegetation dynamics are driven by stochastic climatic events, which result in discontinuous and possibly non-reversible changes. Ecological thresholds, once crossed, offer transition into a number of other possible equilibrium states, distinguished on the basis of community features, plant growth forms or soil properties[11]. In fact, equilibrium and non-equilibrium dynamics are not mutually exclusive, but represent two ends of a continuum within which most systems fall[12]. Depending on spatial and temporal scales, drylands can exhibit both equilibrium and non-equilibrium characteristics, and shifts over time between equilibrium and non-equilibrium dynamics are not uncommon[13].

Due to periodic extreme climatic conditions, drylands were once assumed to be especially fragile in the face of disturbances.[14] However, the view that their evolutionary response to variability increased the resilience of dryland species (Walker et al., 1981; Holling, 1973) has become widely accepted (e.g. Mortimore, 1998). This implies that drylands, though easily perturbed from an initial state of equilibrium, might have a high potential to recover from natural disturbances and might also respond to rehabilitation efforts better than initially believed.

Aridity and Drought

Aridity and drought, both natural features of drylands, need to be differentiated from one another, though in practice they are often confused. While similar in their appearance, both operate at different time scales. Aridity is a long term climatic phenomenon and a defining physical characteristic of drylands. Drought is an episodic feature, which can affect any environment, though is also a frequent and defining characteristic of drylands.

Nature and Causes of Aridity

Aridity is the defining physical characteristic of drylands. It entails not only a permanent rainfall deficit, which is connected also to other climatic phenomena such as

[10] Briske, D. D., Fuhlendorf, S.D. and Smeins, F.E. (2003) Vegetation dynamics on rangelands: a critique of the current paradigms. Journal of Applied Ecology 40, 601-614.

[11] Holling, C. S. (1973) Resilience and Stability of Ecological Systems. Annual Review of Ecology and Systematics 4, 1-23.; Westoby, M., Walker, B. and Noy-Meir, I. (1989) Opportunistic management for rangelands not at equilibrium. Journal of Range Management 42, 266-274.

[12] Wiens, J.A., 1984. On understanding a nonequilibrium world: myth and reality in community patterns and processes, in: D.R. Strong, D. Simberloff, L. Abele, A.B. Thistle (Eds), Ecological Communities: Conceptual Issues and the Evidence. Princeton University Press, N.J., pp. 439--458.

[13] Illius, A. W. and O'Connor, T. G. (1999) On the Relevance of Nonequilibrium Concepts to Arid and Semiarid Grazing Systems. Ecological Applications 9, 798-816.

[14] White, G.F. (ed.) (1956): The Future of Arid Lands. The American Association for the Advancement of Science. Washington DC.

strong insolation, elevated temperatures and high evapotranspiration[15], but is also manifest in a sparse and discontinuous vegetation cover and poorly evolved soils, as soils develop slowly in the absence of water. In addition to a general rainfall deficit, aridity is associated with a high variability and unpredictability of precipitation. Fauna and flora respond to these conditions with a 'pulse-reserve' strategy[16], which entails pulses of activity triggered by rainfall events, such as plant growth. A portion of each pulse is put in to reserve in the form of seeds or energy stores in roots and thus contributes to sustainability during the dry season[17].

Precipitation totals alone do not suffice to define aridity because their significance can only be established relative to temperature and potential evapotranspiration. Over the years, a number of approaches to measure aridity have been put forward[18]. Classical approaches focus on climatic elements and their relationships to vegetation zones; index approaches apply standard formula to define boundaries of the arid zone in terms of annual precipitation and temperature[19]; and water and energy balance concepts portray the relationship between precipitation and evapotranspiration[20].

There is a gradation of aridity from hyperarid to sub-humid regions, which may be disrupted to varying degrees by problems of land degradation and desertification. Categorization of drylands can be made either along the lines of these aridity measurements or in a descriptive way with respect to dominant vegetation forms. Using a simple bioclimatic aridity index, defined as the ratio of precipitation over potential evapotranspiration P/PET, the hyperarid zone corresponds to a P/PET less than 0.03 and marks extreme deserts bare of vegetation except for some annual plants that respond to infrequent rains, and drought-tolerant shrubs in the beds of dry streams where water collects after storms. The arid zone is delineated by P/PET from 0.03 to 0.2 and consists of barren areas or areas covered by sparse vegetation of perennial and annual plants. This zone supports pastoral nomadism but rainfed agriculture is not possible. The semi-arid zone (P/PET: 0.2 – 0.5) is distinguished by open vegetation cover, with perennial species dominating. Extensive livestock grazing can be practiced. In the sub-humid zone (P/PET: 0.5 – 0.75) savannah with or without trees and dry forest prevail and permanent rainfed agriculture with crops adapted to seasonal drought can be practiced[21].

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[15] Mainguet, M. (1999) op cit.
[16] Noy-Meir, I. (1973) Desert Ecosystems: Environment and Producers. Annual Review of Ecology and Systematics 4, 25-51.
[17] Whitford, W. (2002) Ecology of Desert Systems, Academic Press, San Diego.
[18] Beaumont, P. (1993) op. cit.
[19] Köppen, W. (1931) Die Klimate der Erde, Walter de Gruyter, Berlin.; De Martonne, E. (1926) L'indice d'aridité. Bulletin de l'Association Géographique de France 9.
[20] Penman, H. L. (1948) Natural evaporation from open water, bare soil and grass. Proceedings of the Royal Society Sect. A 193, 120-145.; Thornthwaite, C. W. (1948) An approach towards a rational classification of climate. Geographical Review 38, 55-94.
[21] UNESCO (1979) Map of the World Distribution of Arid Regions. UNESCO, Man and the Biosphere (MAB) Technical Notes 7, Paris.

Aridity is associated with a variety of factors, all resulting in blocking moist air masses from reaching an area or inhibiting atmospheric moisture from condensing and falling as precipitation. Descending and divergent air on the downward limb of the tropical Hadley circulation leads to permanent arid conditions paired with high insolation along a belt of subtropical anticyclones (Sahara, Arabian deserts, Thar). In the mid-latitudes, aridity occurs on the lee side of north-south running mountain ranges, which act as barriers for moist oceanic air masses, such as the Sierra Nevada in North America, and in the interior of continents so remote from oceans that air masses reaching there have lost much of their moisture, e.g. in the Central Asian deserts. Anthropogenic aridization has been discussed in the context of desertification, however only a very small portion of today's drylands can be considered truly 'man-made', for example the Aralkum desert surrounding the remainder of the Aral Sea.

Rainfall Variability

Rainfall variability in drylands occurs at different time scales, from seasonal to multi-decadal. As a rule, the lower the annual rainfall totals at a particular location, the higher the variability.

Our understanding of rainfall variability in drylands, particularly with respect to the persistent droughts in the Sahel, has been modified in past decades due to advances in climate observation, monitoring technology, and mathematical modelling. Both temporal and spatial variability in rainfall have come to be understood as a normal part of dryland conditions[22], such that isohyets showing annual averages do not really have much meaning for drylands, because they suggest climate as an equilibrium condition[23].

While the factors driving seasonal variability of rainfall are found in global and regional circulation features linked to the yearly revolution of the Earth around the sun and the tilt of the Earth's axis, the causes of inter-annual and decadal scale variabilities are complex and can be explained by changing configurations of forcings and feedback mechanisms, which, increasingly seem to be induced by atmospheric and ocean circulation dynamics.[24]

Sea surface temperature (SST) anomalies related to the El Niño Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO) or the Pacific Decadal Oscillation (PDO), provide explanations for rainfall variability at different time scales. ENSO cycles, for example, a combination of shifting pressure differences and varying ocean temperatures between the eastern and the western Pacific which occur every few years,

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[22] Glantz, M. H. (1987) Drought and economic development in sub-Saharan Africa. In: Drought and Hunger in Africa: Denying Famine a Future (Ed, Glanz, M. H.) Cambridge University Press, Cambridge.

[23] Hulme, M. (2001) Climatic perspectives on Sahelian desiccation: 1973-1998. Global Environmental Change 11, 19-29.

[24] Barry, R.G. and Chorley, R.J. (1998) Atmosphere, Weather and Climate, Routledge, London.

have consequences not only for the Pacific region – where they are directly correlated with rainfall variability in the Atacama desert – but also have repercussions in other parts of the world via large-scale teleconnections. Nicholson[25] described the relationships between ENSO and rainfall variability in the arid and semi-arid regions of West, East and southern Africa. The PDO is a similar mechanism, but operates at longer time scales of 20 – 30 years and its fingerprints are less visible in West Africa. Barlow et al.[26] analyzed the influence of ENSO on recent droughts in Central and southwest Asia and found a possible linkage between the prolonged duration of a recent ENSO high phase and an exceptionally harsh drought. Myneni et al.[27] found effects of ENSO cycle SST anomalies on temporal rainfall patterns in Africa, Australia and South America.

The explanation of climate variability from large scale modes of atmospheric pressure patterns and sea surface temperatures contrasts with earlier interpretations, which attributed rainfall variability to more regional factors, such as a latitudinal displacement of the Intertropical Convergence Zone (ITCZ) over the Sahel.[28]

Drought

Drought, in contrast to aridity, is an episodic short term phenomenon and as such must be clearly differentiated from aridity. Defined as a period of below average rainfall, it is not restricted to any particular environment, but is particularly associated with drylands, since they tend to experience more variable climate conditions. Although a natural hazard by definition, drought is not only a physical phenomenon but also has an important social component in that its impacts are influenced by drought vulnerability of particular societies or social groups. Therefore, drought is considered by many to be the most complex of all natural hazards[29], the effects of which often accumulate slowly over a considerable period of time and persist longer than the individual event.

Wilhite and Glantz[30] distinguish four kinds of droughts – or disciplinary perspectives – with increasing severity: meteorological, hydrological, agricultural and socio-economic. Meteorological droughts are solely defined on the basis of precipitation departures from average. Hydrological droughts are associated with the effects of precipitation shortfalls on surface and subsurface water supply rather than precipitation

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[25] Nicholson, S. E. (2001) Climatic and environmental change in Africa during the last two centuries. Climate Research 17.
[26] Barlow, M., Cullen, H. and Lyon, B. (2002) Drought in Central and Southwest Asia: La Nina, the Warm Pool, and Indian Ocean Precipitation. Journal of Climate 15, 697-700.
[27] Myneni, R. B., Los, S.O. and Tucker, C.J. (1996) Satellite-based identification of linked vegetation index and sea surface temperature anomaly areas from 1982-1990 for Africa, Australia and South America. Geophysical Research Letters 23, 729-732.
[28] Nicholson, S. E. (2001) op.cit.
[29] Hagman, G. (1984) Prevention Better than Cure: Report on Human and Natural Disasters in the Third World, Swedish Red Cross, Stockholm.
[30] Wilhite, D. A. and Glantz, M. H. (1985) Understanding the drought phenomenon: the role of definitions. Water International 10, 111-120.

shortfalls themselves and usually lag behind meteorological droughts. The definition of agricultural droughts focuses on the crop-specific impacts of reduced water supply for agriculture. Lastly, the term socio-economic drought refers to the cumulative impacts of meteorological, hydrological and agricultural droughts on the functioning of the socio-economic system, for example the supply and demand of some economic goods and services.[31]

On the ground, droughts manifest themselves in vegetation stress and ultimately loss of green vegetation cover, decreases in streamflow, drying out and cracking of soil surfaces. Overall ecosystem productivity declines in times of drought. Although longer term fluctuations of rainfall are seen as a normal part of climate rather than an aberration, the occurrence of prolonged droughts over large areas which caused severe and long-lasting impacts on the ground, such as the great Sahelian droughts, might indicate a regional or even global desiccation trend linked to global climate change. At least in the 20th century, the magnitude and duration of this desiccation has been unprecedented.[32] However, how unique that desiccation has been in the recent human history cannot be established with certainty, because the meteorological record from this area is of relatively short duration.[33]

On one hand, the wet decades of the 1920s 30s 50s might be more exceptional than the dry decades of the post 1960s.[34] On the other hand, it had been suggested that the great Sahelian droughts in particular, require explanations other than natural variability, and that human-induced land degradation might have played a role in exacerbating, if not causing, them because of their long duration and intensity.[35]

Land Degradation and Desertification

Much like aridity and drought, the often-linked pair of terms desertification and land degradation describe phenomena which can be similar in appearance, but are different in scope and time scale. While desertification is restricted to drylands, land degradation can affect any environment. Desertification implies irreversibility at long time scales, whereas land degradation has also been used to describe short-term processes.

Land degradation and desertification are complex phenomena which can be attributed to a number of causes. The contributions of natural, notably climatic, and human factors are difficult to disentangle, and blame has alternately been assigned to

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[31] See Wilhite, D. A. (Ed.) (2000) Drought: a global assessment, Routledge, New York.
[32] Hulme, M., Doherty, R., Ngara, T., New, M. and Lister, D. (2001) African climate change: 1900–2100. Climate Research 17, 145-168.
[33] Nicholson, S. E. (2001) op.cit.
[34] Hulme, M. (2001) Climatic perspectives on Sahelian desiccation: 1973-1998. Global Environmental Change 11, 19-29.
[35] See Charney, J., Stone, P.H. and Quirk, W.J. (1975) Drought in the Sahara: A Biogeophysical Feedback Mechanism. Science 187, 434-435.

anthropogenic and natural processes. A vast literature and the existence of more than a hundred definitions of desertification [36] reflect – or perhaps promote – some of the confusion and controversy surrounding particularly the desertification concept.

According to ‘official’ definitions crafted by the United Nations Convention to Combat Desertification (UNCCD), desertification is “land degradation in arid, semi-arid, and dry sub-humid areas resulting from various factors, including climate variations and human activity”[37], and land degradation is defined as “the reduction or loss of the biological and economic productivity and complexity of terrestrial ecosystems, including soils, vegetation, other biota, and the ecological, biogeochemical and hydrological processes that operate therein … resulting from various factors including climatic variations and human activities”.[38]

These definitions are so broad in scope that virtually any change in land cover conditions, whatever the cause or time period, may be interpreted as land degradation or, in the particular case of dryland environments, desertification. As a result, estimates of the extent of desertification range around one third of the world’s land surface[39], which corresponds approximately to the proportion of arid and semi-arid lands! This obviously debatable figure should be seen as describing an area potentially at risk rather than the area actually affected by desertification. Given their already low biological potential, (hyper-)arid desert cores are less prone to desertification than the semi-arid and sub-humid environments – a fact which should put to rest the image of an advancing desert “tide.” Rather, land degradation starts as small localized pockets in the semi-arid zone.

In view of the importance of non-equilibrium dynamics in arid and semi-arid ecosystems, the concept of ‘degradation’ appears in a different light. In non-equilibrium thinking, moving from one state to another does not necessarily imply degradation. Rather, different states might hold different opportunities for different uses. Reduction of productivity, especially economic productivity, is relative and depends on specific evaluations and objectives, i.e. how this productivity is going to be used and to what end. For example, what constitutes a loss of productivity for the peasant farmer might actually be a gain for the livestock herder.

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[36] Glantz, M. H. and Orlovsky, N. S. (1983) Desertification: A review of the concept. Desertification Control Bulletin 9, 15-22.
[37] UNCCD (1994): Convention to Combat Desertification. p. 4
[38] Ibid. p. 5
[39] See Dregne, H. E. (1983) op.cit. and UNEP (1991) Status of Desertification and Implementation of the UN Plan of action to Combat Desertification, UNEP, Nairobi.

Impacts of Human Activity on Drylands

Especially in popular understanding, land degradation and desertification have commonly been ascribed to adverse impacts of human activity in drylands[40]. Consequently, relationships between people and environment have figured prominently in the research agenda, especially after UNCOD.

Indeed, the bio-physical background of drylands – recurrent droughts and slow rate of soil development – poses some constraints to human land use, which have not always been adequately considered in development schemes. The inherent variability and unpredictability of these ecosystems make them operate as non-equilibrium systems which translate into fluctuating productivity and resource availability. Flexible planning and increased preparedness for droughts and other uncertainties are required, if resources are to be managed sustainably. Traditional land use systems, which have evolved under these constraints, are adapted to cope with the uncertainties imposed by the environment (e.g. shared risk distribution through social relations and opportunistic movement of livestock).[41] Nevertheless, these land use systems have often been unfairly criticized as inappropriate and damaging to their environment.[42]

Generally, the alleged human causes of land degradation and desertification are subsumed under the headings of overgrazing, overcultivation and deforestation, often portrayed as almost inevitable consequences of population growth.[43]

Overgrazing refers to the presence of too many animals on the land so that vegetation cover is locally decreased, permitting the encroachment of noxious and unpalatable grasses and shrubs into pastures, compacting soils by animal trampling, and enhancing the susceptibility to wind and water erosion. Traditional nomadic pastoralism rarely results in overgrazing, however problems arise when mobility is restricted or when subsistence livestock keeping is transformed into commercial production. While declines in vegetation cover may recover quickly once the pressure is removed, secondary effects on the soil resource can have long-term implications and can push the system to a new equilibrium state.

Overcultivation typically consists of a shortening of fallow periods to the point that soil moisture and nutrients are depleted, often accompanied by the expansion of cultivation

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[40] See Mainguet, M. (1991) Desertification: natural background and human mismanagement, Springer Verlag, Berlin.; Mensching, H. (1990) Desertifikation: ein weltweites Problem der ökologischen Verwüstung in den Trockengebieten der Erde, Wissenschaftliche Buchgesellschaft, Darmstadt.; Clarke, J. and Noin, D. (1998) op. cit.; and Le Houerou, H. N. (2002) Man-Made Deserts: Desertization Processes and Threats. Arid Land Research and Management 16, 1-36.

[41] Bruins, H.J. and Berliner, P.R. (1998) Bioclimatic aridity, climatic variability, drought and desertification: definitions and management options. In: The Arid Frontier (Eds., Bruins, H.J. and Lithwick, H.), 97-116.

[42] See Hardin, G. (1968) The Tragedy of the Commons. Science 162, 1243-1248.

[43] Thomas, D. S. G. and Middleton, N. J. (1994) Desertification. Exploding the Myth, Wiley, Chichester.

into marginal lands as lower rates of return require that larger areas be put into production to compensate. Consequences are a loss of biodiversity, accelerated soil erosion, and deterioration of physical and chemical soil properties. Moreover, with farmers moving into marginal lands that do not permanently support rainfed agriculture, pastoralists often find themselves excluded from some of their best grazing grounds and are forced to retreat to even more marginal lands.

Deforestation, driven by demands of fuelwood – the major source of energy in many drylands – and the clearing of land for cultivation also increase exposure and vulnerability to soil erosion,,as root systems are removed and natural wind barriers broken. Even more damage is done when clearing is done by mechanized equipment, which compacts the soil. Indirectly, deforestation might also increase the risk of desertification by contributing to the increase in atmospheric CO_2 while reducing the terrestrial CO_2 sink.[44]

Labelling these land uses as causes of land degradation, however, stems from subjective judgments and is often based on misunderstanding of indigenous land use systems on the part of Western scientists. As a result of their long and intimate contact with their environment, most indigenous people have developed strategies to cope with uncertainties which make economic and ecological sense[45]. Unless droughts hit with unusual severity, these strategies generally help to sustain rather than destroy their resource base[46]. However, socio-economic factors such as poverty, marginality to local power structures, and uncertain or unfavourable land tenure relationships often undermine these strategies.

Although degraded 'sacrifice zones' can frequently be found in the vicinity of settlements and boreholes, regional-scale human-induced degradation is far less common than previously assumed. Thus, Niemeijer and Mazzucato[47] find no conclusive evidence of widespread soil degradation in the West African Sahel. Furthermore, Tiffen and Mortimore[48], echoing Boserup,[49] refute the notion of

[44] See Parry, J.T. (1996) Land degradation in tropical drylands. In: Land Degradation in the Tropics (Eds., Eden, M.J. and Parry, J.T.), 91-97.; and Darkoh, M. B. K. (1998) The Nature, Causes and Consequences of Desertification in the Drylands of Africa. Land Degradation and Development 9, 1-20.

[45] See Mortimore, M. (1989) Adapting to drought. Farmers, famine and desertification in West Africa, Cambridge University Press, Cambridge.; and Scoones, I. (Ed.) (1994) Living with Uncertainty. New Directions in Pastoral Development in Africa, Intermediate Technology Publications, London.

[46] Broad, R. (1994): The Poor and the Environment: Friends or Foes? World Development 22, 811-822.

[47] Niemeijer, D. and Mazzucato, V. (2002) Soil degradation in the West African Sahel - how serious is it? Environment 44, 20-31.

[48] Tiffen, M. and Mortimore, M. (2002) Questioning desertification in dryland sub-Saharan Africa. Natural Resources Forum 26, 218-233.

[49] Boserup, E. (1965) The Conditions of Agricultural Growth. The Economics of Agrarian Change under Population Pressure, George Allen and Unwin Ltd., London.

desertification and show with examples taken from case studies that a growing population can actually contribute to improved soil fertility, tree cover, and water conservation.

No simple relationship between human activity and desertification/land degradation can be established. At short time scales, both natural and anthropogenic stresses can produce similar effects on dryland ecosystems, which makes the relative contributions of drought and human-induced land degradation virtually impossible to separate[50]. Moreover, natural and anthropogenic factors are interrelated in complex ways, which adds to the difficulty of disentangling them. Only the irreversibility of desertification can be used to distinguish it from the relatively short-term effects of drought, which requires long time scale observation to arrive at valid conclusions. Especially in drylands, which often occupy marginal positions with respect to national economic and political centres, reliable long-term records on climate and land use are scarce for many countries, so that to date the tension between anthropogenic and natural causes in the desertification concept remains largely unresolved.

Multiple Linkages and Feedback Mechanisms

Cause and effect relationships between drought, human activities and desertification are neither linear nor simple, but characterized by multiple linkages and feedback mechanisms. While impacts of desertification and land degradation are mostly of local extent, processes which lead to them can be regional or global in nature. Often, a range of factors, both climatic and human, must combine to trigger a process of degradation or to make a land degradation process cross the threshold to quasi-irreversible desertification. To date, these thresholds remain poorly specified, and further empirical research and the availability of long-term data are needed to accurately establish them for specific dryland locations.

Albedo Hypothesis

Otterman[51] and Charney et al.[52] were the first to formulate hypotheses that modification of land cover characteristics in dryland regions might have climatic effects by altering land surface albedo and thus the fraction of incident radiation reflected by the land surface. Their hypotheses argued that desertification actually contributes to drought via a positive feedback mechanism, and not vice versa. Otterman[53] cited the example of the Sinai-Negev region, where the denudation of bright sandy soil by grazing on the

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[50] Nicholson, S. E., Tucker, C.J. and Ba, M.B. (1998) Desertification, Drought, and Surface Vegetation: An Example from the West African Sahel. Bulletin of the American Meteorological Society 79, 815-829.
[51] Otterman, J. (1974) Baring High-Albedo Soils by Overgrazing: A Hypothesized Desertification Mechanism. Science 186, 531-533.
[52] Charney, J., Stone, P.H. and Quirk, W.J. (1975) op.cit.
[53] Otterman, J. (1974) op. cit.

Egyptian side increased albedo and decreased surface temperature compared to the more densely vegetated Negev side. Charney et al.[54] used a global circulation model to show a positive feedback mechanism between a decrease in plant cover and corresponding decrease in precipitation via increasing albedo, radiative cooling of the air column above and thereby an enhancement of large-scale atmospheric subsidence and desiccation. The albedo-hypotheses received broad interest and substantial effort has been made to examine the sensitivity of regional rainfall to large-scale changes in land cover through climate modelling experiments, the results of which support Charney's basic hypothesis that sufficient changes in albedo can, at least potentially, produce droughts. However, satellite measurements of actual sub-Saharan albedo show no evidence for the persistent increase in albedo necessary to produce significant differences in rainfall[55]. Observed changes in albedo due to changes in land surface characteristics have been localized in extent and often short in duration, in contrast to the widespread and sustained changes assumed in the modelling studies. Despite the absence of supporting empirical evidence for the Charney hypothesis, modelling studies are valuable as simulation experiments for understanding the interrelationships between land surface and atmospheric processes.[56]

Role of Atmospheric Dust

The role of dust in affecting precipitation is also controversial. Contrary to what some theoretical models predict[57], Rosenfeld et al.[58] suggest that mineral dust in the atmosphere actually reduces precipitation efficiency of clouds due to the coalescence-suppressing effects of large concentrations of dust particles. In addition, dust can inhibit the formation of convective clouds because of radiative cooling and increased atmospheric subsidence. That would mean that higher dust storm frequency might be the cause rather than the result of the decreased rainfall. Thus, we find that dust emissions from anthropogenic sources might provide a mechanism for initiating a desertification feedback cycle[59]. On the other hand, the dust loading over the Sahel has clearly followed, rather than preceded, trends in precipitation.[60]

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[54] Charney, J., Stone, P.H. and Quirk, W.J. (1975) op.cit.

[55] See Folland, C., Owen, J., Ward, N. and Colman, N. (1991) Prediction of Seasonal Rainfall in the Sahel Region Using Empirical and Dynamical Methods. Journal of Forecasting 10, 21-56.; and Hulme, M. (2001) Climatic perspectives on Sahelian desiccation: 1973-1998. Global Environmental Change 11, 19-29.

[56] Hulme, M. and Kelly, M. (1993) Exploring the links between Desertification and Climate Change. Environment 35, 5-11, 39-45.

[57] Yin, Y., Levin, Z., Reisin, T.G., Tzivion, S. (2000) The effects of giant cloud condensation nuclei on the development of precipitation in convective clouds – a numerical study. Atmospheric Research 53, 91-116.

[58] Rosenfeld, D., Rudich, Y., Lahav, R. (2001) Desert dust suppressing precipitation: a possible desertification feedback loop. Proceedings of the National Academy of Sciences of the United States of America 98, 5975-5980.

[59] Ibid.

[60] Nicholson et al. (1998) op. cit.

The impact of dust on warming is a complex issue, because it modifies both the incoming shortwave solar radiation and outgoing longwave radiation, either a cooling or heating effect can occur, depending on cloud cover and the albedo of the underlying surface.[61]

In addition to its potential impacts on climate, long-range dust transport and deposition influences global biogeochemical fluxes.[62]

Global Warming and Desertification

Over the period of instrumental records, no global long-term trend in rainfall was established, but a CO_2-induced global temperature increase of 0.5° has been observed over the past one hundred years, which has potential repercussions on desertification.

One the one hand, a CO_2-enriched atmosphere is hypothesized to have positive effects on plant growth ("carbon fertilization"), as it can boost photosynthesis and lead to improved water use efficiencies [63] – however, deficiency in soil nutrients could potentially offset positive effects in the long run[64]. On the other hand, an increase in temperature in drylands would increase potential evapotranspiration. Assuming no substantial changes in rainfall, this would lead to desiccation and, in combination with unchanged human use pressure under drier conditions, could ultimately cause desertification. In return, desertification would intensify global warming through the release of CO_2 from cleared vegetation and reduction of carbon sequestration potential of the degraded land.

Whether the CO_2-induced global warming trend would ultimately result in a negative feedback cycle, leading to higher productivity and more efficient water use, or in a positive feedback cycle of increasing aridity and desertification, is difficult to predict.[65]

Conclusion

Land degradation, drought and desertification are linked through complex cause-and-effect relationships, which may be widely quoted but only partially understood. The realization, which has evolved over the past 30 years, that the climatic and ecological

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[61] Nicholson, S. E. (2001) op.cit.
[62] Schlesinger, W.H., Reynolds, J.F., Cunningham, G.L., Huenneke, L.F., Jarrell, W.M., Virginia, R.A. and Whitford, W.G. (1990): Biological Feedbacks in Global Desertification. Science 247, 1043-1048.
[63] Kimball, B.A., Mauney, J.R., Nakayama, F.S. and Idso, S.B. (1993) Effects of increasing atmospheric CO_2 on vegetation. Vegetatio, 104–105: 65–75.
[64] Schlesinger. 2004. Communication at the American Association for the Advancement of Science (AAAS).
[65] Le Houerou, H. (1996) Climate change, drought and desertification. Journal of Arid Environments 34, 133-185.

functioning of drylands is fundamentally different from that of their more mesic counterparts, has only slowly been integrated into the discussion about desertification and land degradation and has rendered some established concepts obsolete.

Although it remains uncontested that land degradation and desertification are interrelated with both drought and human land use practices, the understanding of the nature and relative magnitude of these relationships, which are far more complex than previously assumed, is still rather weak. Marginal areas in terms of global economy, the drylands of the world are also under-researched.

It can be argued that the upsurge in interest in desertification following UNCOD was driven more by politics than science and that its impacts will sort out accordingly. The institutionalization of the desertification issue has offered an opportunity for many dryland nations to garner international attention and support for combating desertification (i.e., attracting economic development) that would not have happened otherwise. However, uncertainties about the scientific basis of our understanding of the processes involved – particularly in the near future – make it difficult to define a clear course of action, paving the way to multiple interpretations and policy orientations.

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APPENDIX C:

RECENT TRENDS IN VEGETATION DYNAMICS IN THE AFRICAN SAHEL AND THEIR RELATIONSHIP TO CLIMATE

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Recent trends in vegetation dynamics in the African Sahel and their relationship to climate

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Abstract

Contrary to assertions of widespread irreversible desertification in the African Sahel, a recent increase in seasonal greenness over large areas of the Sahel has been observed, which has been interpreted as a recovery from the great Sahelian droughts. This research investigates temporal and spatial patterns of vegetation greenness and rainfall variability in the African Sahel and their interrelationships based on analyses of Normalized Difference Vegetation Index (NDVI) time series for the period 1982–2003 and gridded satellite rainfall estimates. While rainfall emerges as the dominant causative factor for the increase in vegetation greenness, there is evidence of another causative factor, hypothetically a human-induced change superimposed on the climate trend.

Keywords: Desertification; Greening; Sahel; Remote sensing; Time series analysis

1. Introduction

The African Sahel, a semi-arid grass- and shrubland region bordering the Sahara desert to the south, is a dynamic ecosystem that responds to fluctuations in climate and anthropogenic land use patterns. Contrary to largely anecdotal assertions of widespread irreversible 'desertification' in the Sahel (e.g. Lamprey, 1975, reprinted in 1988), recent findings based on analyses of satellite images report an increase in greenness over large areas of the Sahel since the mid-1980s, which, at a coarse scale, is well correlated with an overall increase in rainfall and has been interpreted as a recovery of the vegetation from the great Sahelian droughts in the 1970s and 1980s (Tucker and Nicholson, 1999; Eklundh and Olsson, 2003) However, the greening trend is not uniform, suggesting that factors other than rainfall may have contributed to a differential greening response, with greening taking place in some areas but not in others.

Although its actual meaning on the ground has not yet been firmly established, the observed greening trend has challenged notions of irreversible damage inflicted on the Sahelian ecosystem (Dregne, 1983; Middleton et al., 1997), revived debates about the concept of desertification, and triggered re-assessments of its nature, scale and extent, facilitated by progress in remote sensing technology as a tool for environmental monitoring and analysis. However, while studies based on long time series of satellite and ground data have confirmed the dynamic nature of the Sahelian ecosystem and its susceptibility to change, they have not resulted in a consensus on either the direction of changes or its underlying causes.

2. Background

The Sahel (Arabic for 'shore') is a transition zone between the arid Sahara in the north and the (sub-) humid tropical savannas in the south, and is marked by a steep north–south gradient in mean annual rainfall (Le Houerou, 1980). The rainfall gradient is expressed on the ground in

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a continuum of change in vegetation species and life forms from the Saharan biome with very sparse vegetation cover—thorny shrubs interspersed between annual and perennial grasses—to the Sudanian and Guinean biomes, characterized by a higher amount of ground cover, taller vegetation and a greater proportion of woody species (White, 1983). Species thin out and eventually disappear or appear gradually, but 'at no moment would you have the impression of crossing a biological frontier' (Monod, 1985, p. 204).

The climate of the Sahel is characterized by a marked seasonality with a long dry season and a short humid season in the northern hemispheric summer, which is explained by the position of the region relative to major global and regional circulation features and the seasonal variation of tropical weather patterns (Nicholson, 1995). Climatic constraints, i.e. not only scarcity but also variability and unpredictability of rainfall, which increase from south to north, are the most important controlling factors of the Sahelian ecosystem. The vegetation cycle closely responds to the seasonality in rainfall, with virtually all biomass production taking place in the humid summer months. The sharp seasonal contrasts are overlain by considerable fluctuations in rainfall at inter-annual and -decadal time scales, which make the Sahelian region the most dramatic example of climate variability that has been directly measured (Hulme, 2001). Causes for long-term rainfall fluctuations are complex and can be found in changing configurations of forcings and feedback mechanisms, which can be induced by atmospheric and ocean circulation dynamics with global-scale effects, such as the El Nino southern oscillation (ENSO) cycles (Nicholson, 2001; Nicholson and Grist, 2001), non-ENSO-related variations in sea surface temperatures (Giannini et al., 2003; Brooks, 2004), and large-scale changes in land cover and land–atmosphere interactions (Charney et al., 1975; Hulme and Kelly, 1993; Nicholson, 2000; Hulme et al., 2001; Zeng et al., 1999). Furthermore, a number of modeling studies point to possible links between Sahelian rainfall variability and anthropogenic global warming (e.g. Eltahir and Gong, 1995; Giannini et al., 2003).

Although variability in rainfall and the occurrence of droughts are seen as normal phenomena in arid and semi-arid climates (Glantz, 1987), rendering mean annual rainfall figures almost meaningless (Hulme, 2001), the droughts that affected the Sahelian region in the late 1960s through the 1980s following a series of favorable years were unprecedented in this century in their length and impact. Land degradation and famine conditions during these droughts, exacerbated by political instability and unrest, have triggered an upsurge in interest in the issues at work in the Sahel and appropriate countermeasures that might be taken, resulting in the United Nations Conference on Desertification (UNCOD) in 1977. The conference has prompted an ongoing and still unresolved debate about the causes and effects of drought, land degradation and desertification (Herrmann and Hutchinson, 2005). Two competing camps represent diametrically opposed positions in this debate: while adherents of the desertification hypothesis hold human activities responsible for a—hypothetically irreversible—decline in vegetation conditions in the Sahel, expressed as 'overuse of resources' and 'human mismanagement' (Mensching, 1990; Mainguet, 1991; Ibrahim, 1978), desertification skeptics interpret declines in vegetation condition and density as drought-induced and hence temporary phenomena, with humans playing only a minor role, if at all (Nicholson et al., 1998; Olsson et al., 2005). Mortimore and Adams (2001), Tiffen and Mortimore (2002) and Reij et al. (2005) report local-scale 'success stories' and stress the high potential of adaptation of the Sahelian population to rainfall variability in time and space. A growing archive of satellite observations has indeed shown a close coupling between vegetation greenness and rainfall variability. Tucker and Nicholson (1999) found the green vegetation boundary of the Sahel to fluctuate by up to 150 km from a wet year to a preceding dry year in response to rainfall. With such great natural fluctuations, the permanence of land degradation in the form of desertification can only be established by monitoring susceptible areas over a time scale of decades.

Ecosystem monitoring, in the Sahel and elsewhere, has been facilitated by progress in remote sensing technology and the availability of data sets at ever finer spatial, temporal and spectral resolutions. Remote sensing presents important advantages to the monitoring of vegetation dynamics and land degradation—such as the synoptic perspective it offers—however, there are limitations to this technology that also have to be taken into account. As a synergistic tool, remote sensing does not unfailingly distinguish between different vegetation types and, therefore, might hide changes in vegetation cover not associated with changes in overall greenness, such as shifts in vegetation composition. Other limitations arise from the technological and cost-induced trade-offs between different types of resolution, such that simultaneous increases of spatial, spectral and temporal resolutions, all of which can provide more precise information in different aspects of vegetation dynamics, in one system are inhibited (Cihlar, 2000).

3. Objectives and rationale

In light of the ongoing debate about the driving forces of vegetation dynamics and land degradation in the Sahel and the still insufficient distinction made between the effects of drought and 'desertification', the objectives of this research were to (1) further explore the relationship between climatic and anthropogenic causes of land degradation at a coarse resolution, (2) break down trends in precipitation and vegetation dynamics into spatial patterns and (3) identify hotspots of potentially human-induced land degradation as well as rehabilitation for further study at finer spatial resolution.

The relationship between vegetation and rainfall in semi-arid environments has received a great deal of interest, notably in the African Sahel. Most previous regional-scale studies were based on time series of remotely sensed indicators of vegetation greenness, mainly the Normalized Difference Vegetation Index (NDVI), and rainfall measurements from ground stations. Nicholson et al. (1990) found a linear relationship between rainfall and NDVI in the Sahel below a rainfall threshold of about 1000 mm/year. The correlation between the two variables was found sufficiently strong to use NDVI as a proxy for mapping rainfall variations (e.g. Tucker and Nicholson, 1999). Prince et al. (1998) used rain use efficiency, a ratio between net primary production and rainfall, to characterize vegetation response to rainfall and found an upward trend over most of the Sahel for the period 1982–1990. Significant increases in vegetation greenness, in phase with increasing rainfall, were noted by Eklundh and Olsson (2003), who studied trends in NDVI amplitude and time-integrated NDVI for the period 1982–1999. While all these studies refute claims of widespread desertification in the Sahel at a coarse resolution and indicate overall positive developments in both vegetation and rainfall since the mid-1980s, few efforts have been made to explicitly disentangle the effects of climate/rainfall and human impact on vegetation dynamics in the Sahel.

This research, building on findings of previous studies about the nature of the relationship between rainfall and vegetation greenness in the Sahel, carries the analysis of this relationship one step further to address the question of a possible 'human signal' in vegetation dynamics. It is hypothesized that, if there is any significant human signal detectable at the coarse resolution of 8 km in addition to the climate signal, it would show in the residuals after removal of the climate signal from the NDVI data set.

4. Data sets

4.1. Normalized Difference Vegetation Index

The NDVI was employed in this study as a proxy for vegetation greenness. The data is derived from measurements made by the Advanced Very High Resolution Radiometer (AVHRR) instrument on board the National Oceanic and Atmospheric Administration (NOAA) polar orbiting satellite series. The NDVI, a normalized ratio of the near-infrared and red spectral reflections (NIR−red/NIR + red), is sensitive to the presence, density and condition of vegetation and is correlated with absorbed photosynthetically active radiation (PAR) and vegetation primary production. It exploits the different spectral characteristics of bare soil and green vegetation in the red and near-infrared portions of the electromagnetic spectrum, with reflectance in the red decreasing with increasing chlorophyll absorption and reflectance in the near-infrared increasing with increasing green plant biomass (Tucker, 1979; Rouse et al., 1974; Tucker et al.,1985, Myneni et al., 1995). The NDVI is the oldest remotely sensed vegetation index in use and remains, despite its shortcomings (sensitivity to soil color, atmospheric effects, illumination and observation geometry), the most widely used by the remote sensing community. The development of alternative vegetation indices—the Soil-Adjusted Vegetation Index (SAVI) (Huete, 1988), the Modified Soil-Adjusted Vegetation Index (MSAVI) (Qi et al., 1994), the Atmospherically Resistant Vegetation Index (ARVI) (Kaufman and Tanre, 1992) and the Enhanced Vegetation Index (EVI) (Huete et al., 2002)—aimed at minimizing some of these problems, has not resulted in the creation of a consistent time series for universal application.

A monthly NDVI time series for the period 1982–2003 was taken into consideration. Data for the year 2004 were omitted from the study because of scan motor problems of the AVHRR-16, which produced bar code noise and resulted in data of poor quality (http://www.oso.noaa.gov/poesstatus/). NOAA AVHRR satellite sensors have been operational for more than two decades and offer a length of record that is unmatched. However, the AVHRR NDVI time series is afflicted with some non-negligible errors induced by the lack of on-board band calibration, atmospheric effects differing between the respective bands and variations in solar illumination and sensor view angles produced by satellite overpass time drifts (e.g. Slayback et al., 2003). Yet, the effects of satellite drift on NDVI are rather small in sparsely vegetated biomes: for the Sahel, 2% of the variance of NDVI could be explained by the solar zenith angle effect (see Pinzon et al., 2004, Table 1). The NDVI time series used here is an 8 km spatial resolution monthly maximum value composite processed by the Global Inventory Modeling and Mapping Studies (GIMMS) Group at NASA's Goddard Space Flight Center (Tucker et al., 2005), in which the above-listed biases have been minimized or eliminated. In particular, the GIMMS NDVI has been corrected for residual sensor degradation and sensor intercalibration differences, effects of changing solar zenith and viewing angles, volcanic aerosols, atmospheric water vapor and cloud cover using nonlinear empirical mode decomposition methods (Pinzon et al., 2004; Huang et al., 1998) and maximum value compositing to minimize cloud contamination (Holben, 1986). As a result, the GIMMS NDVI data set used in this study is relatively consistent over time and shows a high level of precision for semi-arid and arid areas. In comparison with other NDVI data sets—Pathfinder Land (PAL) and Global Vegetation Index (GVI)—and previous versions produced by the GIMMS group, the new GIMMS NDVI has been found to be of superior quality (Brown et al., 2003).

4.2. GPCP and TRMM gridded precipitation estimates

Rainfall measurements from rain gauge stations are conventionally considered the most accurate and reliable source of rainfall data; however, this is only true for point measurements or areas with a sufficiently dense network of rain gauges. Throughout most of the Sahel, rain gauges are sparse and of varying reliability, and measurements not always easily available (Adeyewa and Nakamura, 2003; Nicholson et al., 2003a). As a proxy for rainfall, gridded satellite precipitation estimates were used in this study, which combine satellite observations from different sources and ground measurements where available into area-averaged precipitation fields. The principles behind these merged data sets, which exploit the strengths of each of the data sources to improve the overall quality of precipitation estimation, and the combination methodology are explained in more detail in Xie and Arkin (1995, 1997), Ardanuy and Arkin (1989) and Adler et al. (2003). The GPCP Version2 combined precipitation data set produced monthly by the Global Precipitation Climatology Project (GPCP) at 2.5° spatial resolution was used for the period 1982–2003. In addition, the merged product 3B43 from the Tropical Rainfall Measuring Mission (TRMM) available at 1° spatial resolution for the shorter period 1998–2003 served as a means of validation of the GPCP-based results. The GPCP product integrates, in weighted averages, infrared observations from the Geostationary Operational Environmental Satellite (GOES), Geosynchronous Meteorological Satellite (GMS) and Meteosat with microwave estimates from the Special Sensor Microwave Imager (SSM/I) and rain gauge data (Adler et al., 2003; Janowiak, 1991). The TRMM algorithm 3B43 combines three independent precipitation fields from the TRMM instrument package—the monthly average TRMM Microwave Imager (TMI) estimate, the monthly average Special Sensor Microwave/Imager (SSM/I) estimate and the pentad-average adjusted merged-infrared (IR) estimate—with the monthly accumulated Climate Assessment and Monitoring System (CAMS) or GPCP rain gauge analysis (Kummerow et al., 2000).

Although some satellite-only-based rainfall estimates are plagued with considerable bias over much of the African continent, the merged products which include ground measurements seem to be of superior quality. The performance of TRMM has been validated over Africa (Adeyewa and Nakamura, 2003) and West Africa in particular (Nicholson et al., 2003b) and the merged product 3B43 was found to be very well correlated with rain gauge measurements. McCollum et al. (2000) and Nicholson et al. (2003a) showed that the GPCP combined precipitation data set also out-performed the individual component satellite products. In general, the estimates are expected to be more reliable for the relatively politically stable western Sahel region than for the central and eastern Sahel, where a decline in ground measurements due to economic and political instability is likely to induce bias.

5. Methodology

The spatial–temporal analysis of the dynamics and trends in rainfall and vegetation greenness during the study period 1982–2003 is based on a sample size of 264 months, whereas the sample size of the shorter period 1998–2003 (validation period) amounts to 72 months. A definition of the Sahel region was derived from a 20-year-average NDVI rather than average annual precipitation as in Tucker et al. (1991), i.e. the Sahel was delineated by a minimum NDVI of 0.15 and a maximum of 0.4, which corresponds to the region with the steepest north–south gradient in vegetation greenness. However, any attempt to delineate the Sahel region by using long-term averages does not do justice to its fluctuating boundaries.

5.1. Pre-processing

Pre-processing of the NDVI time series had already been accomplished by the GIMMS group (see Section 4.1). For further analysis, the 8-bit GIMMS NDVI was converted into real NDVI. The gridded GPCP and TRMM precipitation data sets were re-projected to Albers Conical Equal Area Projection and resampled to match the 8 km resolution NDVI data set. While this procedure replicates a large number of GPCP pixels of the same value with no gain in spatial resolution in this data set, it enables to retain the finer spatial resolution of the NDVI data. Average daily (GPCP) or hourly (TRMM) precipitation rate estimates were converted into series of monthly and overlapping 2- and 3-monthly rainfall totals for later correlation and regression analyses with different time lag intervals.

5.2. Computation of trends

In order to determine spatial patterns of directions and rates of change, overall trends in NDVI and rainfall were computed for both the study and validation periods by fitting simple linear functions through the time series of each pixel and calculating the trend slopes. For the purpose of visualization, these were converted into changes in NDVI throughout the study period and expressed in percentage relative to the value of the linear trendline at the starting point of the time series.

5.3. Linear correlation and regression analyses

In order to test the strength of linear association between rainfall and NDVI, Pearson's correlation coefficients were computed for the two variables for each pixel with different time lags: NDVI versus rainfall of the current month with no time lag, NDVI versus cumulative rainfall of the current plus the previous month, and NDVI versus cumulative rainfall of the current plus the two previous months. The strongest linear correlation having been confirmed for NDVI and 3-monthly cumulative rainfall (consistent with findings of Nicholson et al., 1990), a linear regression analysis was carried out with NDVI as the dependent variable and 3-monthly cumulative rainfall as the independent variable. Local differences in the NDVI–rainfall relationship due to prevailing soil and vegetation types (Nicholson and Farrar, 1994) and their respective rain use efficiencies are taken into account by computing intercepts and slopes individually for each pixel. The regression equations establish a causal relationship between dependent and independent variables and allow the calculation of predicted values of maximum NDVI for each month and each pixel from the observed precipitation values.

NDVI residuals, the difference between observed and predicted NDVI, were then computed for each month and each pixel as done by Archer (2004) and Evans and Geerken (2004). The residuals represent that part of the observed NDVI value which is not explained by rainfall, provided that the computed linear regressions are accurate descriptions of the causal relationship between rainfall and NDVI for each individual pixel. In a scatter plot, they are represented by the distance of each point to the regression line. Residuals are assumed to contain noise, as well as, if present, the influence of any causative variables other than rainfall, which had been left out in the regression model. Any significant temporal trends in the residuals would point to an error of omission of a salient variable. To test for any long-term human-induced effects on vegetation greenness, be it positive (regeneration, re-forestation) or negative (desertification), trends were computed on the time series of NDVI residuals. The trend slopes were mapped in order to assess spatial patterns. As a measure of significance of the calculated trends, they were compared to their sigma errors and all trends exceeding the respective sigma error were labeled significant.

5.4. Extraction of temporal profiles

From the mapped trends in the residuals, hot spots displaying significant positive or negative trends were identified and temporal profiles of observed and predicted NDVI and NDVI residuals extracted for selected pixels (e.g., Figs. 6 and 7) and the dynamics of observed and predicted NDVI compared.

5.5. Validation

Validation of this regional-scale analysis is a difficult endeavor due to the large extent of the study area, and a field campaign to selected locations within the identified hot spots is planned for the next phase of this research stage of the project, with the aim of collecting detailed information on vegetation composition and land use and management. Thus far, a preliminary validation is obtained by comparing results of residual analyses based on a regression with GPCP and TRMM data for the validation period 1998–2003.

6. Results and discussion

6.1. Overall trends

For the period 1982–2003, the overall trend in monthly maximum NDVI is positive over a large portion of the Sahel region (Fig. 1), reaching up to 50% increase in the average NDVI in parts of Mali, Mauritania and Chad. It is understood, however, that averages are not very meaningful in this highly dynamic environment where considerable seasonal fluctuations around the mean are the norm. This result confirms previous regional-scale findings for the period 1982–1999 by Eklundh and Olsson (2003) and Olsson et al. (2005), who observed widespread positive trends of both time-integrated NDVI and NDVI amplitudes, and Anyamba and Tucker (2005), who maintained increases in growing season NDVI across most parts of the region. It is also in keeping with the global increase in net primary production due to climate change, postulated by Nemani et al. (2003). The positive trend in monthly maximum NDVI is accompanied by widespread increases in rainfall over the same period of time, with maximum positive slopes in northern Nigeria (Fig. 2). However, from a longer-term perspective, the observed increase can merely be interpreted as a return to more or less 'average' rainfall conditions that prevailed before the 1960s after an exceptionally dry period and does not even suffice, across the entire region, to cancel out the secular downward trend

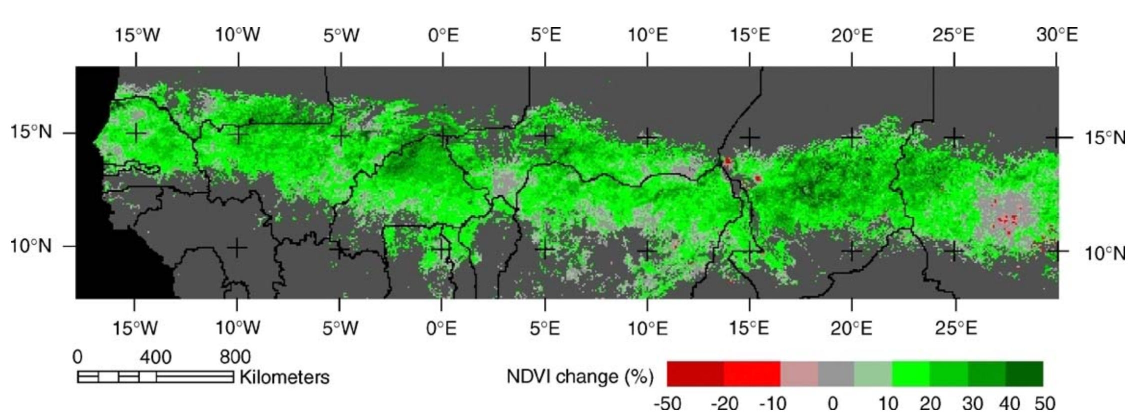


Fig. 1. Overall trends in vegetation greenness throughout the period 1982–2003 based on monthly AVHRR NDVI time series. Percentages express changes in average NDVI between 1982 and 2003.

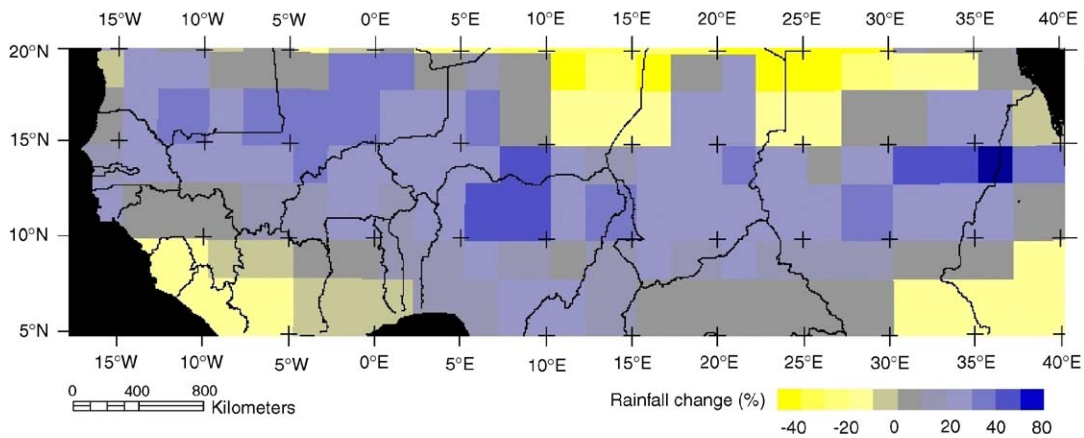


Fig. 2. Overall trends in monthly rainfall throughout the period 1982–2003 based on GPCP estimates. Percentages express changes in average GPCP-estimated rainfall between 1982 and 2003.

in rainfall (Hulme et al., 2001; Hulme, 2001; Nicholson, 2004). Indeed, the early- to mid-1980s saw the peak of Sahelian desiccation of this century, so that any analysis departing from there is on the rising limb of interannual and -decadal rainfall variability.

6.2. Correlation between NDVI and rainfall

Monthly maximum NDVI in the Sahel was found to be correlated best with rainfall accumulated over a period 3 months (current plus previous 2 months), which confirms earlier findings by Justice et al., 1986; Nicholson et al., 1990; Lotsch et al., 2003 and others that vegetation greenness in semi-arid environments is more strongly related to soil moisture, a function of rainfall accumulated over a period of time, than to instantaneous rainfall.

Correlation coefficients computed for NDVI and GPCP and TRMM exceed those found by Nicholson et al. (1990) based on rain gauge data, which might as well be a function of the NDVI data set employed. They are highly significant for the entire Sahel region ($P<0.05$), with stronger correlations in the southern Sahel than in the north. However, the presence of autocorrelation in both NDVI and rainfall data sets, which is a common phenomenon in time series and expresses persistence of variables, is likely to affect statistical relations and induce overestimation of the correlation coefficients (Granger and Newbold, 1974; Phillips, 1986). Durbin–Watson test statistics calculated for selected points yielded values between 0.4 and 0.7, all of which were significant ($P<0.01$) and confirm autocorrelation in the data sets. Although this phenomenon has possibly affected the magnitude of the correlation coefficients, it is not expected to have changed the overall spatial pattern of correlations (Fig. 3).

The zone of the highest correlation between NDVI and rainfall defines the extent of the semi-arid zone, where rainfall is the most important constraint to vegetation growth, while in the arid zone to the north, both variables are negligible and in the humid zone to the south, moisture availability is not the principal limiting factor for vegetation growth—hence, the zonality in correlation coefficients. Areas within the semi-arid zone where moisture availability is more a function of exogenous stream flow, such as the Niger delta, stand out of the zonal pattern by their lower correlation coefficients.

6.3. Residual analysis

The spatial pattern of trends in the NDVI residuals reveals large areas without significant trends, i.e. areas in which actual trends in vegetation greenness correspond closely to what is expected from the trends in rainfall dynamics, and considerable areas of positive residual trends, i.e. areas in which the vegetation has been greening up more than explained by rainfall alone (Fig. 4). These ‘positive hot spots’ are spatially coherent and comprise, among others, parts of Senegal, Mauritania, Mali, Niger, the Central Plateau of Burkina Faso and large portions of Chad. While the greening in the Niger delta of Mali might be explained by an expansion of irrigation, different explanations must be found for the Central Plateau of Burkina Faso, which had been identified as a prime example of the desertification crisis some 20 years ago (Pearce, 2002). Here, a recovery of vegetation greenness beyond what would be expected from the recovery of rainfall conditions alone might be due to increased investment and improvements in soil and water conservation techniques, such as contour bunding, in response to the drought crisis experienced by farmers (Reij et al., 2005). The importance of human factors, including decisions on production strategies and land use, in contributing to environmental and vegetation changes at long time scales is also stressed by Rasmussen et al. (2001) in an analysis of vegetation development on fossil dunes in northern Burkina Faso.

In Niger, positive trends in NDVI residuals are observed in the Tahoua and Maradi regions, centering around the area of ‘Projet Keita’, an extensive rural development

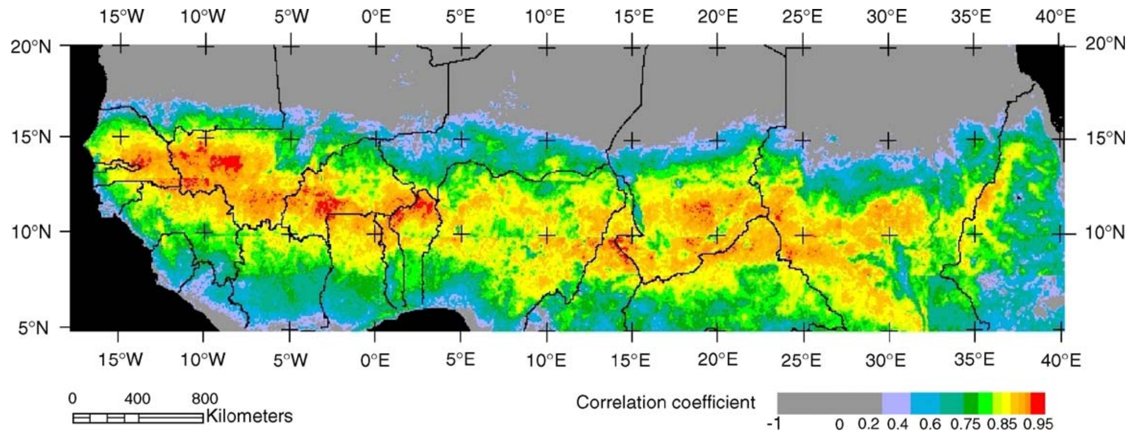


Fig. 3. Linear correlations of monthly NDVI with 3-monthly cumulative rainfall based on GPCP estimates for the period 1982–2003. Note that both variables are highly correlated in the Sahel region.

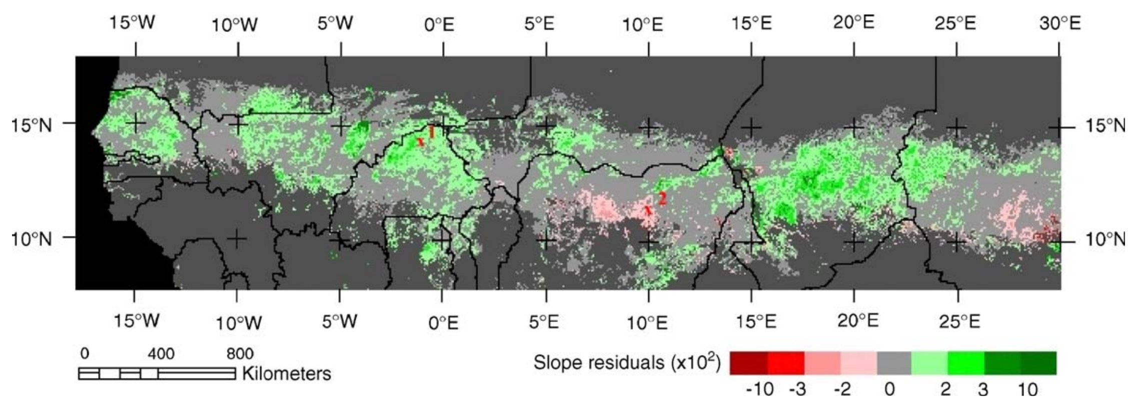


Fig. 4. Overall trends in the residual NDVI throughout the period 1982–2003 based on regression of vegetation greenness (AVHRR NDVI) on 3-monthly cumulative rainfall (GPCP estimate). Slopes of residual NDVI trendlines between 1982 and 2003 are expressed in units of NDVI $\times 10^4$. Locations of sites 1 and 2 are indicated, for which temporal profiles (Figs. 6 and 7) were extracted.

program with a focus on natural resource management and soil and water conservation which began in the early 1980s supported by the Food and Agriculture Organization (FAO) and the World Food Program (WFP) of the United Nations as well as the governments of Niger and Italy (FAO, 1994). Evidence of farmer-managed natural regeneration in this region of Niger was also confirmed by Chris Reij (personal communication, 2004), particularly along the road between Maradi and Dosso. In Chad, vegetation greening was observed among other places in the Chari–Baguirmi region, where the West African Pilot Pastoral Program has managed a few sites since 1994 to test a participatory approach to holistic rangeland management, the outcome of which was positively evaluated by pastoralists (Reij and Steeds, 2003).

Pixels showing negative trends in the NDVI residuals cover a considerably smaller area of the Sahel and are clustered in northern Nigeria and Sudan. Here, vegetation greening has fallen behind what would be expected from the increase in rainfall, which has been particularly sharp in northern Nigeria. A hypothetical explanation of what might be interpreted as human-induced land degradation in these areas is the neglect of good land use practices due to civil strife and conflict. Fig. 5 highlights that the trends found in the residuals are significant over most of the area, with insignificant results coinciding, as expected, with areas showing negligible trends in the residuals.

Temporal profiles extracted for selected pixels representative of positive, negative and negligible trends in the residuals (Figs. 6 and 7) show that removing the effects of rainfall from the NDVI time series did not completely remove the seasonality, part of which may be attributed to the seasonality in other environmental factors such as temperature. A comparison of predicted and observed vegetation dynamics illustrates, in the case of a Burkina Faso location, the gradual 'overtaking' of the predicted NDVI by the observed NDVI, notably in the peaks. The example of northern Nigeria shows a reverse dynamic, with the observed NDVI progressively falling behind the predicted one, both in the peaks and valleys of the profile. Owing to the characteristics of a less arid climate, the dynamics of vegetation greenness is smoother and displays less year-to-year variability in the example from northern Nigeria than in the example from Burkina Faso. The trends

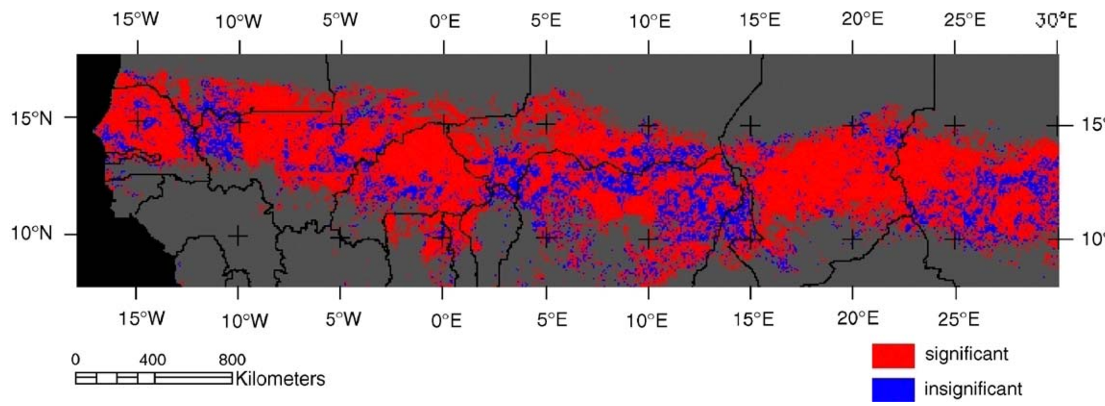
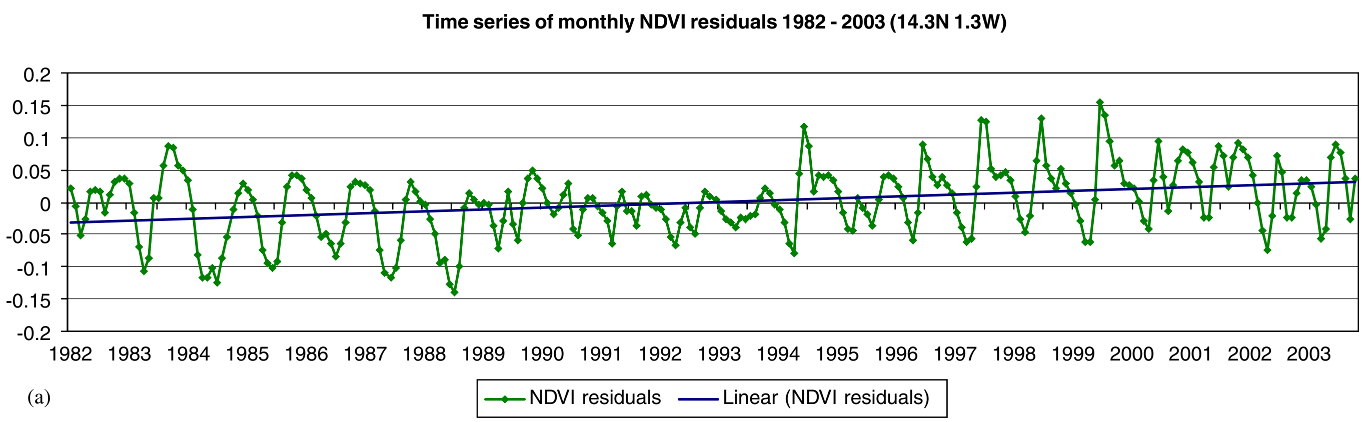


Fig. 5. Significances of trends in the residual NDVI time series show significant results over most of the study area. Trends are termed 'significant' for pixels in which trend slopes exceed the respective sigma errors and 'insignificant' for pixels in which sigma errors exceed trend slopes.



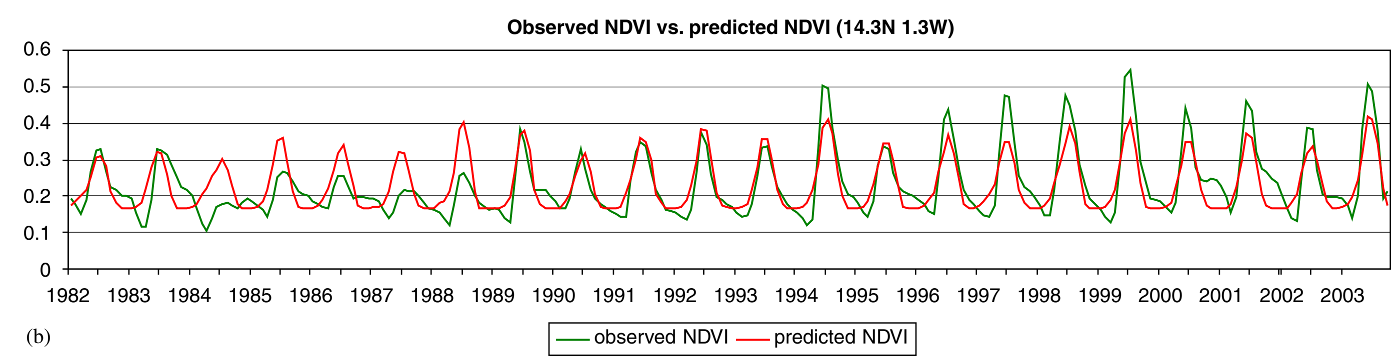


Fig. 6. Temporal profiles for location (1) (see Fig. 4) with significant positive trend in the residual NDVI (Central Plateau, Burkina Faso). (a) Residual NDVI time series and linear trendline. (b) Time series of observed and predicted NDVI.

found in the residuals, however, cannot be attributed to zonal effects, as an analysis of a number of temporal profiles from different latitudes revealed (not shown).

6.4. *Comparison of results based on GPCP and TRMM*

Rainfall trends for the period 1998–2003, whether based on GPCP or TRMM data, differ from rainfall trends for the longer period 1982–2003 in that negative trends are present in the northernmost parts of the Sahel, notably extending from the northern Tahoua region in Niger to the east. Droughts intensified in these regions during the past 5 years, whereas the central and southern parts of the Sahel experienced mostly increasing rainfall (see also Nicholson, 2005). Correspondence between the two data sets is high, with correlation coefficients ranging from 0.9 to 0.99, which can be explained by the fact that both data sets rely on input data partly from the same sources (see Section 4.2).

Consistent with the observed trends in rainfall for the period 1998–2003, the respective NDVI trends show a decrease in vegetation greenness in a band along the

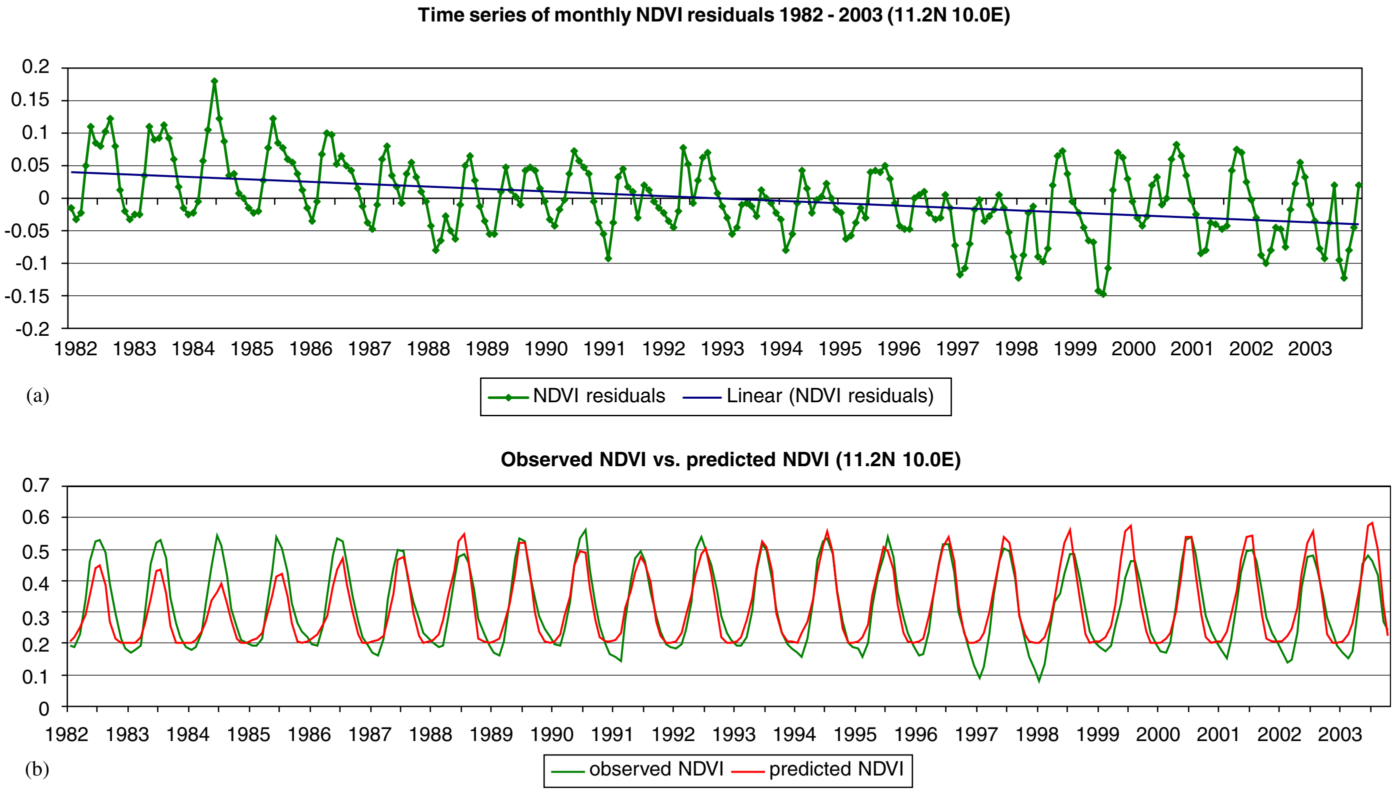


Fig. 7. Temporal profiles for location (2) (see Fig. 4) with significant negative trend in the residual NDVI (northern Nigeria). (a) Residual NDVI time series and linear trendline. (b) Time series of observed and predicted NDVI.

northern margin of the Sahel (Niger, Chad and Sudan). This trend, however, is not as well defined as the trend for the longer time series, since it comprises only the period of 'most greening'.

The trends in NDVI residuals, after removing the effects of rainfall from the NDVI data set, display very similar spatial patterns for regression analyses based on either GPCP or TRMM. Although these trends for 1998–2003 are not statistically significant over most of the area—i.e. the trends themselves are smaller than the sigma error, the main point here is to show the close agreement between results based on different sources of rainfall estimates, which can be seen as a means of validation of the methodology and increases the confidence that the NDVI residuals and trends therein contain more than just random noise.

7. Conclusions

This research adds to a series of coarse-resolution studies on the Sahel which refute claims of widespread human-induced land degradation at a regional scale, e.g., Prince et al. (1998), Tucker and Nicholson (1999); Hellden (1991) and Eklundh and Olsson (2003). Rather, a greening of the Sahel expressed in positive trends in NDVI indicates a net increase in biomass production during the period 1982–2003, which challenges the notion of irreversible desertification in the Sahel. Whether this greening trend is a return to pre-drought conditions or a transition to a new equilibrium state with a different vegetation composition, however, is unclear and can only be established with detailed field work at local scale and analysis of finer resolution spatial data from LANDSAT and MODIS.

Rainfall emerges as the dominant causative factor in the dynamics of vegetation greenness in the Sahel at an 8 km spatial resolution. However, the presence of spatially coherent and significant long-term trends in the residuals suggests that there might be another, weaker, causative factor. Since the Sahel is a 'cultural landscape' (Rasmussen et al., 2001), which is driven not only by climatic but also human factors, it is conceivable that the trends found in the residuals might be attributed to a 'human signal', as evidence from the literature suggests for particular regions (see Section 6.3). While short-term impacts such as pests can cause rainfall-independent deviations of the NDVI in individual years, long-term trends are more likely to be induced by human factors, such as changes in land use, exploitation of natural resources, production strategies and conservation efforts. Field studies in selected sites are required to confirm this hypothesis and to contribute to the understanding of processes and causes at work in particular local contexts.

Throughout most of the Sahel, there are no signs of large human-induced land degradation at this scale of observation—which does not mean that pockets of land degradation are not present at local scales. Only parts of northern

Nigeria and Sudan show areas where human impact hypothetically inhibited a greening trend in the order of magnitude expected from the positive trend in rainfall conditions.

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APPENDIX D:

EXPLORING RELATIONSHIPS BETWEEN RAINFALL AND VEGETATION DYNAMICS IN THE SAHEL USING COARSE RESOLUTION SATELLITE DATA

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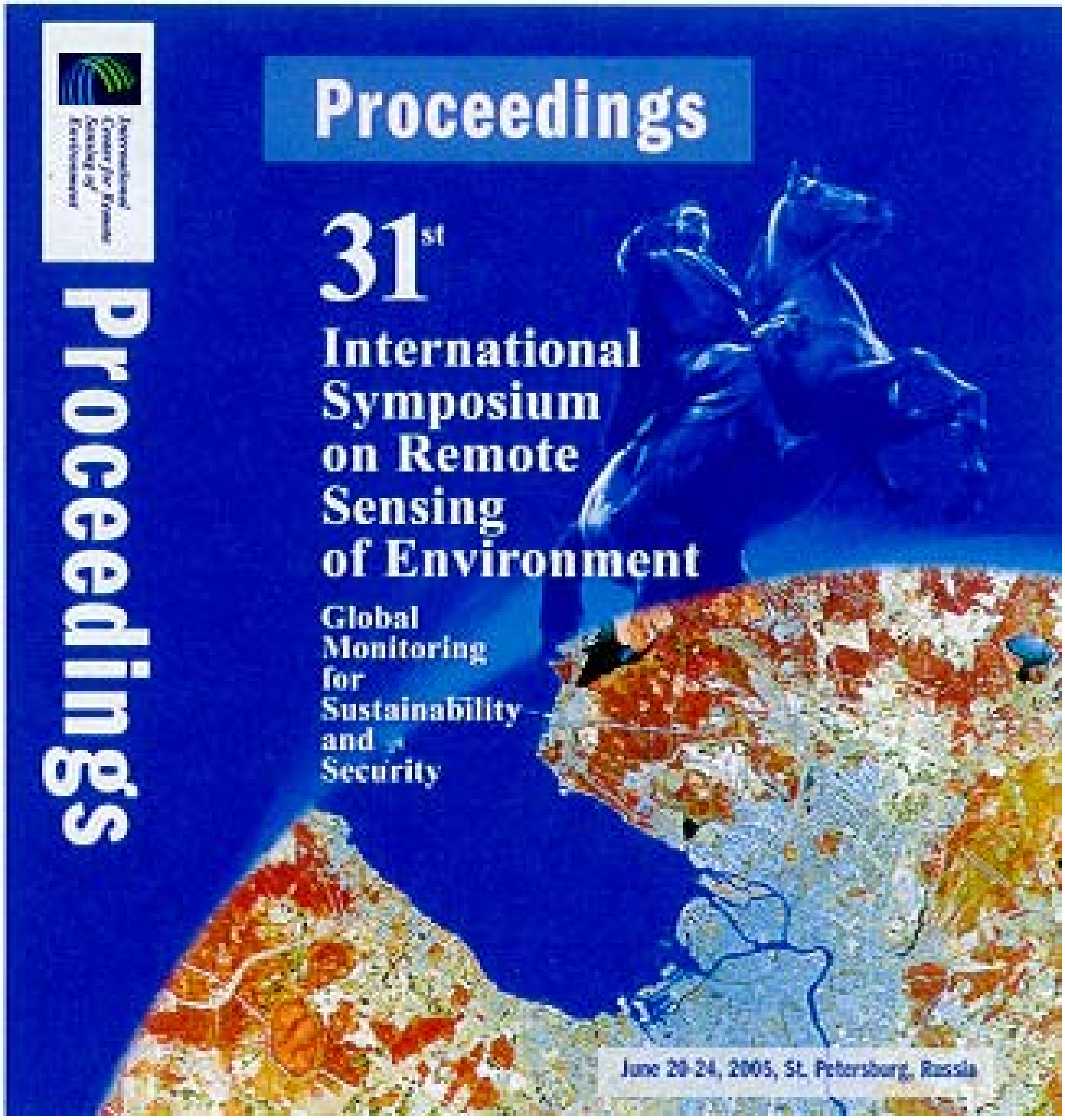
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Exploring Relationships between Rainfall and Vegetation Dynamics in the Sahel Using Coarse Resolution Satellite Data

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Abstract – This research investigates temporal and spatial patterns of vegetation greenness and explores relationships between rainfall and vegetation dynamics in the Sahel, based on analyses of NDVI time series and gridded precipitation estimates at different spatial resolutions.

Keywords: rainfall, vegetation, land degradation, Sahel

1. INTRODUCTION

The West African Sahel, a semi-arid transition zone between the arid Sahara in the north and the subhumid tropical savannas in the south, is a dynamic ecosystem that responds to fluctuations in climate and anthropogenic land use patterns. The climate of the Sahel is characterized by a marked contrast between a long dry season and a short humid season in the northern hemispheric summer, with increasing scarcity, variability and unpredictability of rainfall from south to north. Although variability in rainfall and recurring droughts are normal phenomena of the semi-arid climate, the droughts that affected the Sahelian region in the late 1960s through the 1980s were unprecedented in this century in length and impact (e.g. Tucker and Nicholson, 1999). Famine conditions and land degradation became widespread during these droughts, the latter being frequently interpreted as irreversible change or ‘desertification’. However, contrary to largely anecdotal assertions of wide-spread ‘desertification’ in the Sahel (e.g. Lamprey, 1975 [reprinted 1988]), recent findings based on analyses of satellite images report an increase in greenness over large areas of the Sahel since the mid 1980s, which has been interpreted as a recovery of the vegetation from the great Sahelian droughts (e.g. Tucker and Nicholson, 1999; Eklundh and Olsson, 2003). This recently observed greening trend has challenged notions of irreversible damage inflicted on the Sahelian ecosystem and renewed the debate about the concept of desertification (Herrmann and Hutchinson, 2005), in which two diametrically opposed positions are represented by those who see human mismanagement as the root cause of irreversible desertification (LeHouerou, 2002) and those who refute the concept of desertification altogether and stress the importance of natural fluctuations in rainfall and consequently vegetation response (Tucker and Nicholson, 1999; Eklundh and Olsson, 2003).

While the relationship between vegetation and rainfall in semi-arid environments has been studied extensively, particularly in the Sahel, few efforts have been made to explicitly disentangle the effects of rainfall and human impact on vegetation dynamics. The objectives of this research are to further explore trends in vegetation greenness and precipitation and their spatial patterns in the Sahel and to address the question of a potential ‘human signal’ in vegetation dynamics by developing a method of removing the climate signal from vegetation greenness time series.

2. DATASETS USED

2.1 Vegetation greenness data

Vegetation greenness is expressed by the Normalized Difference Vegetation Index (NDVI), a remotely sensed measurement of spectral reflections in the red and near-infrared wavelength regions [(NIR-red)/(NIR+red)] sensitive to the presence, density and condition of green vegetation. The NDVI is the common and, despite some shortcomings, most widely used vegetation index. Therefore, relatively continuous long term time series starting in the early 1980s are available. In this study, we used NDVI datasets from two different satellite sensors: the Advanced Very High Resolution Radiometer (AVHRR) sensor on board the National Oceanographic and Atmospheric Administration (NOAA) polar orbiting satellite series and the Système Probatoire pour l’Observation de la Terre Végétation sensor (SPOT/VGT).

NOAA AVHRR sensors have been operational for more than two decades and offer a length of record that is unmatched. We used an 8-km spatial resolution monthly maximum value composite of the NDVI for the period 1982 to 2003, preprocessed by the Global Inventory Modeling and Mapping Studies (GIMMS) Group at NASA’s Goddard Space Flight Center. This NDVI time series has been corrected for residual sensor degradation and sensor intercalibration differences, effects of changing solar zenith and viewing angles, volcanic aerosols, atmospheric water vapor and cloud cover, using nonlinear empirical mode decomposition methods (Pinzon et al., 2004).

The SPOT Végétation (VGT) sensor has only been operational since 1998 on two SPOT missions (http://vegetation.cnes.fr/). The VGT NDVI product used in this study differs from the AVHRR NDVI in its finer spatial resolution of 1 km, narrower band widths in the red and NIR wavelengths meant to enhance vegetation discrimination, and the minimal preprocessing of the dataset compared to the AVHRR NDVI time series (e.g. monthly maximum value compositing but no atmospheric corrections).

2.2 Precipitation estimates

Since rain gauges are sparse and of varying reliability throughout the Sahel (Nicholson et al., 2003), this study employed gridded satellite precipitation estimates, which combine satellite observations from different sources and available ground measurements into area averaged precipitation fields. The principles behind these merged datasets and the combination methodology are explained in more detail in Xie and Arkin (1997).

For establishing a relatively long term relationship between rainfall and vegetation greenness, a combined precipitation dataset from the Global Precipitation Climatology Project at a spatial resolution of 2.5° (GPCP Version 2) was used for time period 1982-2003. The GPCP product integrates, in weighted averages, infrared observations from the Geostationary Operational Environmental Satellite (GOES), the Geosynchronous Meteorological Satellite (GMS) and METEOSAT with microwave estimates from the Special Sensor Microwave/Imager (SSM/I) and rain gauge data (Adler et al., 2003).

The 10-day rainfall estimates (RFE), produced by NOAA/CPC (Climate Prediction Center) to support the USAID/FEWS (Famine Early Warning System) project in drought and flood risk monitoring for Africa, provided a shorter term, but finer spatial resolution gridded rainfall dataset. The RFE are based on Meteosat satellite data, Global Telecommunication System (GTS) rain gauge reports, and microwave data from the SSM/I and the Advanced Microwave Sounding Unit (AMSU) (Xie and Arkin, 1997). A combination of versions 1.0 and 2.0 of the dataset allowed the creation of a 0.1° resolution time series that matches the length of the VGT NDVI record.

3. METHODS

3.1 Establishing coarse-scale rainfall-NDVI relationships for the period 1982 to 2003

Since 3-month cumulative rainfall had already been found to be correlated best with NDVI for the region under study (Herrmann et al., 2005 ; consistent with findings of Nicholson et al., 1990), the rainfall estimates from GPCP and RFE were converted into a time series of monthly overlapping 3-month cumulative totals and resampled in order to fit the spatial resolution and geographic projection of the NDVI time series.

With the aim of establishing a causal relationship between rainfall and NDVI, a linear regression analysis was carried out for the entire Sahel on the longest available time series, with the AVHRR NDVI as the dependent and the GPCP cumulative rainfall totals as the independent variable. Local differences in the NDVI-rainfall relationship due to prevailing soil and vegetation types are taken into account by computing intercepts and slopes individually for each pixel. The regression equations allow the calculation of predicted values of NDVI for each month and each pixel from the observed precipitation values.

NDVI residuals, the difference between observed and predicted NDVI, were then computed for each month and each pixel (Archer, 2004). The residuals present that part of the observed NDVI value which is not explained by rainfall, provided that the computed linear regressions are accurate descriptions of the causal relationship between rainfall and NDVI for each individual pixel. They are assumed to contain noise, as well as, if present, the influence of any causative variables other than rainfall, which had been left out in the regression model. Temporal trends in the NDVI residual time series were calculated and mapped with the aim of establishing areas in which significant trends in the residuals would point to an error of omission of a salient variable.

3.2 Application of the method to finer-scale datasets for the period 1998 to 2003

In order to test the possibility of expanding the analysis to higher spatial resolution datasets, with the drawbacks of their limited temporal availability, a comparison of higher and lower resolution NDVI and rainfall data was carried out at the example of seven selected locations. To that end, temporal profiles were extracted from all datasets, which had previously been regridded to a spatial resolution of 8km.

The AVHRR NDVI and the VGT NDVI time series were compared and correlated against each other in order to show agreement and discrepancies of the two data sets from different sources. The same was done for the two rainfall estimates, as well as different combinations of rainfall versus NDVI. Predicted NDVI time series were calculated using the linear regression between NDVI and rainfall established from the longer time series (see 3.1) and linear regressions calculated from the shorter time series. The coefficients of these regressions were compared to each other in order to evaluate the applicability of the rainfall-NDVI relationship determined using the longer, coarse-resolution time series, which is assumed to be more accurate due to the length of the record, to the shorter, but higher spatial resolution, time series of VGT NDVI and RFE rainfall estimates. Differences between observed VGT NDVI values and NDVI values predicted from RFE rainfall using the linear relationship established from AVHRR NDVI and GPCP rainfall estimates were calculated and compared to the residuals as computed in 3.1.

4. RESULTS AND DISCUSSION

4.1 Summary of findings from the coarse scale assessment

Overall positive trends in NDVI and rainfall over the period 1982 to 2003 were confirmed. Linear correlations between the two variables were found to be highly significant throughout the entire Sahel. Indeed, rainfall is the most important constraint to vegetation growth in this semi-arid zone, which justifies the attempt to predict vegetation greenness from rainfall estimates through linear regression (Herrmann et al., 2005).

The spatial pattern of trends in the NDVI residuals (Fig.1, last page), computed by subtracting observed from predicted NDVI values, reveals large areas without significant trends, i.e. areas in which actual trends in vegetation greenness correspond closely to what is expected form trends in rainfall dynamics, and considerable areas of positive residual trends, i.e. areas in which the vegetation has been greening up more than explained by rainfall alone. These areas comprise parts of Senegal, Mauritania, Mali, the Central Plateau of Burkina Faso, southern Niger and large portions of Chad. While the greening in the Niger delta of Mali might be explained by an expansion of irrigation, different explanations must be found for the Central Plateau of Burkina Faso, which had been identified as a prime example of the desertification crisis two decades ago (Pearce, 2002). Here, a recovery of vegetation greenness beyond what would be expected from the recovery of rainfall conditions alone might be attributable to increased investment and improvements in soil and water conservation techniques (e.g. Reij et al., 2005).

Negative trends in the NDVI residuals are clustered in northern Nigeria and Sudan. Here, vegetation greening has fallen behind what would be expected from the increase in rainfall. A hypothetical explanation of what might be interpreted as human-induced land degradation in these areas is the neglect of good land use practices due to civil strife.

4.2 Preliminary results from comparison of different datasets

Comparison of observed rainfall and vegetation dynamics from 1998 to 2003 showed marked differences between AVHRR and VGT NDVI as well as GPCP and RFE rainfall estimates, which are summarized in Figure 2. Overall, the VGT NDVI tends to be higher than the AVHRR NDVI and the GPCP rainfall data higher than the RFE. These differences, rooted in differences in data collection, resolution and calibration, are neither spatially nor temporally consistent and make a direct transfer of the rainfall-NDVI relationship computed from one dataset to the other problematic.

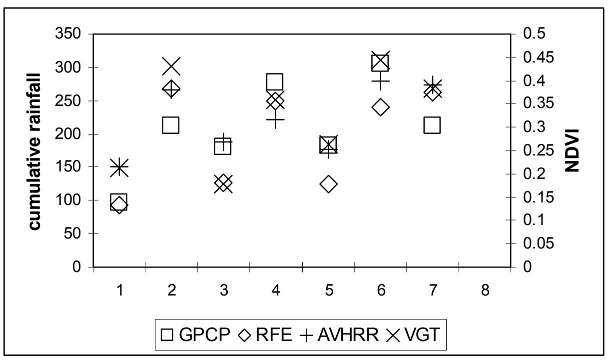

Figure 2. Average NDVI and cumulative rainfall for 7 selected sites during the period 1998-2003

The linear relationships between rainfall and NDVI for the period 1998 to 2003 tended to be similar for GPCP versus AVHRR and RFE versus SPOT for some points (Fig.3a, last page), encouraging the use of the supposedly more reliable regression equation based on the longer time series, but quite different for others (Fig.3b), making the use of this regression equation impossible. The same is true for the temporal pattern of the difference between observed and predicted NDVI for GPCP versus AVHRR and RFE versus SPOT.

5. CONCLUSIONS

From the coarse scale assessment, rainfall emerges as the dominant causative factor in the dynamics of vegetation greenness in the Sahel. However, the presence of spatially coherent and significant long-term trends in the NDVI residuals suggests that there is another, weaker, causative factor, possibly a 'human signal'. However, field studies in selected sites are required to confirm this hypothesis.

The results of the preliminary comparison of GPCP versus AVHRR and RFE versus VGT relationships are still inconclusive and require further study. The inconsistency in the results point to the need for cross-calibration between different sensors and datasets, if are to be used in combination.

6. ACKNOWLEDGEMENTS

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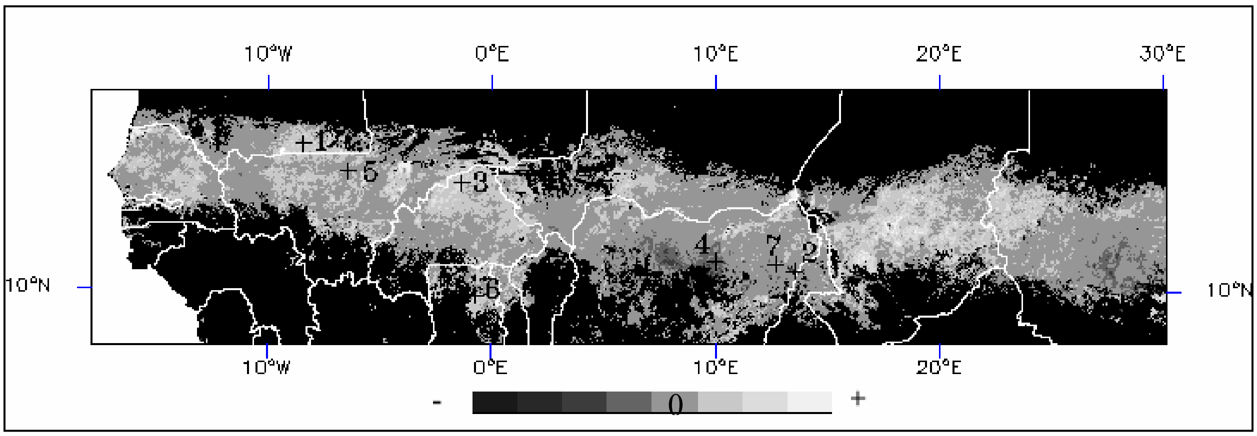

Figure 1. Overall trends in the residual NDVI time series throughout the period 1982 to 2003, based on regression of vegetation greenness (AVHRR NDVI) on three-monthly cumulative rainfall (GPCP estimate). The seven selected locations for which time series were extracted are indicated with +. Definition of the Sahel region is based on a 20-year NDVI average of 0.15 to 0.4.

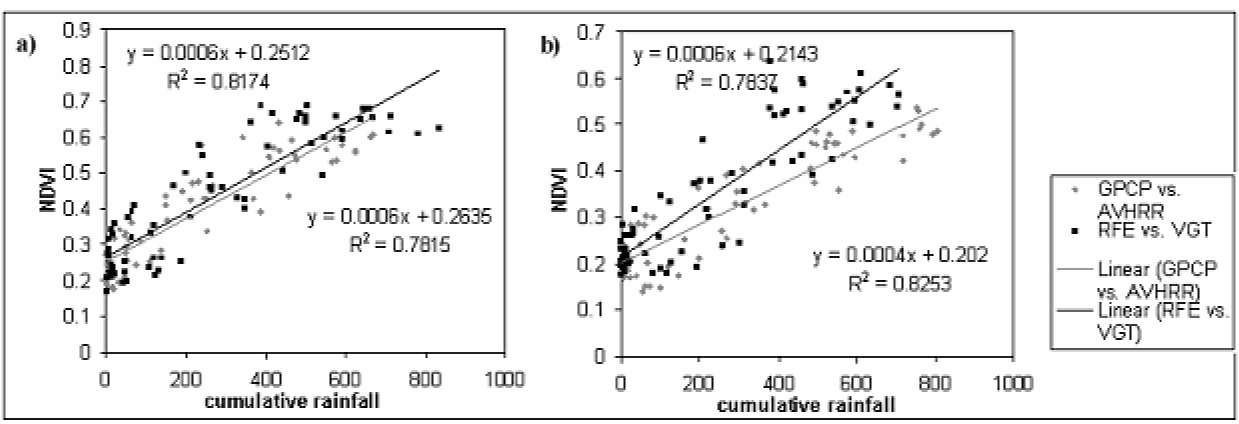

Figure 3. Linear regressions between GPCP rainfall and AVHRR NDVI in comparison with linear regressions between RFE rainfall and VGT NDVI for locations #2 (a) and #4 (b).

APPENDIX E:

DESERT OUTLOOK AND OPTIONS FOR ACTION

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DESERT OUTLOOK AND OPTIONS FOR ACTION

This chapter considers alternative futures for deserts in the coming decades. These futures depend both on how we manage the deserts and on global economic developments and environmental policies. Taking into account trends in the numbers of the people, their demands on resources and changes in climate, this chapter explores scenarios of changes in water resources, biodiversity and land degradation. The chapter closes with a section on the policy options that could lead towards sustainable management of desert resources and the enhancement of human well-being in deserts.

Scenarios of change

The record of unanticipated events in recent decades testifies to the difficulties in foreseeing the future. Political events, such as the collapse of central planning, economic changes (for example, the spread of market economies and the increasing globalization of economies), technological breakthroughs (for example, the coming of the information age and the emergence of the internet), and unpredictable epidemiological challenges (as with HIV/AIDS) help to explain profound gaps between the predicted and the observed. Particularly for desert ecosystems, whose most predictable feature seems to be unpredictability, forecasts are both hard to make and fallible.

Despite their inherent imperfections, scenarios of alternative futures have become an important tool for defining the range of possible futures for society and environment. These "lessons from the future" have proved to be indispensable for identifying the needs for action, and the possible consequences of alternative actions, and may thus prompt changes in policy. A prominent example is the prediction of forest dieback as a consequence of acid rain that was made in the 1980s for Europe and North America. The projected cataclysm brought about large reductions in SO_2 emission. Partly as a result, the prediction of dramatic forest dieback never materialized (UN/EC 2001).

Like other models, scenarios are based on assumptions about cause-and-effect relationships among different elements of a system. The outcomes of scenarios depend on the identification of the major driving forces of change and specifications of how they, directly or indirectly, might affect the ecosystem concerned. Unlike some modeled systems, desert ecosystems are non-linear and have a high degree of variability, patchiness and unpredictability. These characteristics make scenario-building and analysis particularly challenging. Moreover, many deserts are not well studied, because they are marginal to national economies: both environmental and economic data are seldom as available at the same resolution, quality or length-of-record as they are in more humid and more densely populated areas.

While this chapter focuses on environmental changes in deserts, many of their driving forces operate at a global scale. Likewise, some desert processes have global implications. Thus, a change in the albedo of a desert surface and dust emissions from deserts may affect global atmospheric dynamics. Out-migration from deserts – whether it be politically, environmentally or economically motivated – increases pressures in non-desert biomes.

Driving forces for foreseen changes

The driving forces are grouped here into two: human population growth and global climate (Warren and others 1996). We can predict with some confidence that the human population will continue to grow, albeit at decreasing rates, both globally and in deserts (United Nations Population Division 2005). The implications of growth for prosperity, environmental and developmental trends are more difficult to predict. An increasing body of observations indicates global warming, which may have repercussions on precipitation. There is compelling evidence that most of the warming is attributable to human activities, largely the emission of greenhouse gases. Based on alternative emission scenarios, a range of possible warming scenarios have been built, all of which predict further increases in global temperature, but with differing magnitudes (IPCC 2001). These driving forces are not independent but strongly related. Thus, population growth and economic development influence concentrations in greenhouse gases and thereby global climate. Both are projected to rise, particularly as the world's largest populations – India and China – rapidly industrialize. Changes in climate have already affected many natural environments, and there are indicators of impacts of climate changes on social and economic systems in many, if not most parts of the world.

Population dynamics

During the past century, the world has seen an unprecedented increase in human population. Although the rate of growth has begun to slow, growth continues. By 2050, the world population will probably count two to four billion people more than today and be more urban (United Nations Population Division 2005). Global statistics, however, mask important disparities. Most growth will take place in the less developed regions. In contrast, some highly developed regions have already experienced reductions in fertility and could see a considerable demographic decline unless their populations are replenished by in-migration. Regardless, the message is clear: more people, most in cities in the developing world.

Because of the constraints of aridity, deserts are among the least densely populated regions of the globe. According to the United Nations Development Program, only 6 per cent of the world population live in the arid and hyperarid zones, which cover 20 per cent of the global land area (UNDP 1997). The vast majority of desert dwellers, 94 per cent according to Noin (1998), live in the developing countries, where population growth rates are among the highest.

Since the beginning of the 20th century the population in the deserts of the developing world has multiplied by a factor of eight, and since 1950, by four (LeHouérou 2002). Most population growth in deserts takes place in the cities, where livelihood opportunities are concentrated. The proportion of urban population is already very high in those desert countries in which a modern economy has a strong secondary and tertiary sector, as in Libya (86.9 per cent), Saudi Arabia (88.5 per cent), Bahrain (90.2 per cent), The United Arab Emirates (85.5 per cent), Israel (91.7 per cent) and Qatar (92.3 per cent). In other desert countries, agriculture is the dominant sector and urbanization is still comparatively modest (as in Pakistan: 34.8 per cent; Uzbekistan: 36.4 per cent; Somalia: 35.9 per cent; Niger: 23.3 per cent), but growing at a rapid pace (for example, the urban population in Niger is predicted to increase by a factor of four in the next 25 years), while rural population numbers are projected to remain more or less stable (United Nations Population Division 2005).

Most desert populations have an age structure typical of many developing countries with high proportions of young people. As a result of this skew toward the younger cohorts, population will continue to increase, even if fertility rates decline. The age structure also has important economic implications, such as labor availability, demand for education, and the size and nature of markets. The deserts of the United States, which record the highest population growth rates in the country (Sutton and Day 2004), display a reverse age structure due to the importance of retirement migration into the "Sunbelt".

Two major demographic uncertainties in the projections of population include international migration and family structure (for example the age of mother at the birth of her first child, the number and spacing of children) (Cohen 2003). Movement of people is difficult to predict, as it responds to rapidly changing economic, political and environmental factors. While much environmental migration is towards less arid and more predictable environments ("greener pastures"), people may also move into more arid areas if they offer better security, as in the case for some of the displaced people in the current Darfur conflict. By adding population to already strained infrastructure, migration can be a source of additional pressure and make resource management more challenging. Changes within the resident population are slower, but are as difficult to predict. They result from a complex interplay of culture, society and economics. Thus, the model of demographic transition (Notestein 1945), that described the transformation of populations from high birth and death rates to low birth and death rates in Europe, has very limited explanatory or predictive value outside the western world (Kirk 1996). In the developing world, there appear to be more female-headed households, which are a product of the migration of men seeking employment in urban areas. The long-term consequences of these family disruptions are not yet well understood. It might be presumed that, at least initially, there might be realignment towards urban, maledominated populations and rural populations of children, the elderly and female-headed households.

Demand for Resources

As population increases, the demand for basic resources – water, food, energy, shelter – must rise. Since an important part of the population growth in deserts takes place in the developing world, where there are high rates of economic growth, the demand for resources there is expected to rise at a higher rate than population. With increasing *per capita* income and urbanization, consumption patterns tend to adjust and converge with those in developed countries. For example, the use of domestic water in the urban households in those parts of the developing world that have access to running water is significantly higher than in rural households (Roudi-Fahimi and others 2002). Economic growth also spurs energy consumption, which is notably affected by structural changes in the economy and activity in each economic sector. Typically, as economies grow, they go from a prevalence of agriculture, which has a low energy demand, through a phase of energy-intensive industries to a prevalence of lighter energy-efficient industries and services, accompanied by constant increases in energy demand in the transport sector (Alcamo, 1996).

Economic development not only imposes additional pressures on resources, it can also bring about shifts in the kinds of resources that are demanded. Fuelwood may be replaced by higher-grade forms of energy, such as oil or gas – or even nuclear – with different implications for the environment. Some of the resources that are scarce in deserts, such as water, food or building material, can be imported, given a certain level of economic development. This might ease the pressure on the immediate desert environment, but increases cumulative global resource demand. However, economic growth also means that more resource-efficient technologies can be afforded, such as more sophisticated irrigation systems, treatment and reuse of wastewater, use of energy sources that are alternatives to local fuelwood, and the purchase rather than the household production of milk and meat.

Thus, economic development not only increases demand for resources because of changes in consumption, but also holds the potential for sustainable resource management, if coupled with a favorable and stable political environment.

Climate variability and change

Over the 20th century, global average surface temperatures increased by about 0.6°C. This was the largest temperature increase in any century in the past 1,000 years. The warming has been attributed to anthropogenic emissions of greenhouse gases associated with forest clearance beginning in the 18th century, and the consumption of fossil fuels which accompanied industrialization in the 19th-century. This last process is likely to continue through the 21st century, so that increases in atmospheric CO_2 concentrations are projected to continue (IPCC 2000). Depending on the assumed emission scenario (see Box 6.1), a globally averaged temperature increase of 1.4 to 5.8°C is expected over the period 1990 to 2100.

Global warming has important implications for the water cycle. Increases in temperature have already driven changes in rates of evaporation and evapotranspiration, precipitation, soil moisture, water storage in snowpacks, and flow regimes of rivers. Water plays a central role in desert life: the abundance of vegetation and biodiversity are primarily governed by the availability of soil moisture; so are human livelihood opportunities, directly and indirectly. Hence, it has been argued that desert environments will be very responsive to the impacts of global warming (Lioubimtseva and Adams 2004).

While all the climate models predict increases in global mean precipitation, some regions will become wetter and others drier, and there are large differences in these projections between different climate models (van Boxel 2004). For example, a study by Held and others (2005) predicted a drying trend in the Sahel over the next 50 years as a result of global warming and increases of aerosols in the atmosphere, whereas Haarsma and others (2005) expected that the warming of the Sahara might bring increased rainfall in the adjacent Sahel. Both models are global simulations, and the large differences in their outputs result from uncertainties in the boundary conditions they adopt (such as emission scenarios) and the processes they choose to model (such as respective roles of clouds, oceans, greenhouse gases in determining the disposition of solar energy). Irrespective of rainfall, increases in evaporation and evapotranspiration resulting from higher temperatures will increase the potential for more severe, longer-lasting droughts in deserts.

As a general trend, there have already been reports of increases in the variability of rainfall and in the frequency of extreme events (Salinger 2005). Interannual rainfall variability caused by the ENSO (El Niño Southern Oscillation) and NAO (North Atlantic Oscillation) cycles is likely to increase further, which will reinforce the pulse and reserve dynamics governing desert ecosystems, triggering potentially fewer but more intense biologically significant rainfall pulses. There is evidence that higher drought incidence is likely to reinforce, or at least expose, desertification/degradation processes (LeHouérou 1996), such as permanent losses of bioproductivity and biodiversity, erosion and deflation – and could lead to the spread of some processes that have been assumed to be under control, such as the re-mobilization of vegetated sand dunes (see Box 6.2).

Box: Re-mobilization of relict dune fields

Increasing aridity, as a result of complex repercussions of twenty-first century global warming, could turn some semi-arid rangelands into deserts and cause the re-mobilization of relict dunes that are currently stabilized by vegetation.
Simulation experiments by Thomas and others (2005), based on a variety of global climate change models, suggested that some of the stabilized dune systems in the southern African Kalahari basin could be reactivated by way of decreases in soil moisture and increases in the number of extreme climatic events. Both factors boost the 'dune mobility index', a measure of potential sediment mobilization combining surface erodibility (vegetation cover and soil moisture) and atmospheric erosivity (wind energy). Independent of the specific climate change model that these authors used, their simulations predicted significant enhancement of dune mobility in the southern Kalahari dune fields by 2039 and in the eastern and northern dune fields by 2069.
Other relict dune fields, which could potentially experience climate-induced re-mobilization in the coming decades, include Australian and North American dunefields (Knight and others 2004).

Some of the water in some deserts comes from rivers that originate outside the desert boundary, often in the snow and ice packs of high mountains. For example, the Colorado River, which brings water to the arid American Southwest, is fed by summer snow-melt in the Rocky Mountains, and the Central Asian deserts receive water from rivers which rise in the Himalayas and Central-Asian mountains (see Box 6.3). Ice and snow in these mountains constitute an important reservoir of water, which slowly releases water during the summer months. Global warming has already reduced the thickness and extent of snow packs and caused seasonal shifts in stream-flow. The projected increases in temperature over the coming decades will have serious impacts on the hydrological cycle and regional water supply, by affecting accumulation and duration of snow cover, rate of melting and long-term water storage in glaciers (Barnett and others 2005). By way of global teleconnections, changes in pressure systems in different parts of the globe can have hydrological implications for deserts. Thus, Archer and Fowler (2004) found a significant relationship between the variability of NAO and winter precipitation in the Karakorum, which can be useful in predicting summer runoff in the Indus basin.

Box: Scenarios for snowpack in High Asia

As one of the largest glaciated areas on Earth, the Tibetan Plateau together with the surrounding Himalayan mountains plays an important role in freshwater storage and provides water to the adjacent Central Asian deserts in the north (Kara-Kum, Kyzyl-Kum, Takla-Makan) and the Thar and Rajasthan Deserts in the south by way of rivers fed by glacier runoff. Irrigated agriculture along the Amu Darya, Syr Darya and Tarim rivers in the Central Asian deserts as well as in the Indus Basin irrigation system depends heavily on water originating in High Asia (Winiger and others 2005).

Böhner and Lehmkuhl (2005) estimated the current extent of glaciers in High Asia from aerial photographs and satellite images, and modeled the potential decreases of glacial area by predicting the magnitudes of climate change under alternative socio-economic emission scenarios (IPCC 2000). Their results showed small changes in precipitation but considerable increases in annual mean temperature for High Asia (1° – 1.8°C by the end of the 21st century in the best case scenario and 3.8° – 6°C in the worst case scenario), which exceed global average rates of increase. Given the high sensitivity of the snow and ice cover to warming, the projected temperature increase has severe consequences for the glaciated area, which would decrease by 42.5 per cent in the best case and by 81.4 per cent in the worst case scenario. In the latter case, continuous ice cover would be limited to the Himalaya, Karakorum, Pamir and West Kunlun, whereas the Qinling Shan and Tien Shan mountain ranges would be left almost without glaciers. In addition, the slow thawing of permafrost areas and their transformation into peat bog in the more humid areas might in turn enhance global warming as a result of methane emissions.

Globalization

Globalization, defined as the increasing worldwide integration of markets for goods, services, labor and capital, is a major driving force of economic and environmental change, with potentially dramatic and unforeseeable impacts on development and environmental change in deserts. The past few decades have been characterized by a general shift from protectionism and state-dominated economies to freer trade and privatization; from local and national scale economic activities to increased international flows of capital, information and goods; and from a strict dependence on local natural resources to a growing importance of technology, infrastructure and institutions for development (Di Castri 2000). Globalization has not evolved linearly, but has moved forward unevenly with major discontinuities. The geopolitical opening that coincided with the end of the Cold War, the economic and financial openings defined in the General Agreement on Tariff and Trade, and the opening of a global information society with the establishment of the Internet have all greatly accelerated global homogenization and interconnectedness. In response, a counter-trend of increased cultural diversification, revival of local languages and indigenous identities has sprung up in many places in an overt attempt to offset the homogenization that some feel is a consequence of globalization.

The temporal non-linearity and geographic patchiness of globalization make projecting its future extremely difficult. However, its implications for the causation, or solution, of environmental problems are enormous and are frequently overlooked in purely environmental studies. On the one hand, globalization (especially the spread of free market economies) has the potential to increase economic disparities and widen social gaps, within and among countries. A further marginalization of desert economies would have grave consequences for the environment, as poverty forces people to forego proactive and sustainable resource management in the pursuit of immediate survival (Panayotou 2000). On the other hand, new opportunities to enhance economic development while improving environmental conditions can emerge in globalization. Although environmental issues, particularly the lack of water, will continue to play a role in development if globalization proceeds, they will likely become less decisive than the economic and human factors that will be increasingly mobilized to overcome them, such as innovation, infrastructure, marketing of assets/available resources. Diversification of the economy that reduces reliance on (subsistence) agriculture on marginal lands, might follow from the enlargement of markets and new marketing opportunities and ease pressure on resources and environment.

Narrative and quantitative scenarios

As alternative images of the future, scenarios assist in understanding how complex systems might perform. Scenarios are not predictions or forecasts; many variables and inter-relationships within and among natural and social systems are insufficiently understood, so that precise predictions are not possible. Uncertainties arise from the quality of the data that are used, the incomplete understanding of the functioning of a system, and approximations and generalizations made in the scenario building process (IPCC 2000). Nevertheless, scenarios are useful tools for scientific assessment and for policy making because they provide a focus for discussion, help to organize statements about the future, and point out critical trends that could jeopardize sustainable development (Raskin 2005). Scenarios generally have a narrative component in the form of a story, and a quantitative component represented by a numeric model that may illustrate and support the story. Some systems are well understood and can be supported by appropriate quantitative data; others are better communicated by descriptive stories. In practice most scenarios combine both (Kok and Delden 2004).

Water

Water is a critical resource for human development and environmental health, particularly in deserts. Many desert countries are facing serious water shortages. According to thresholds proposed by Falkenmark and Widstrand (1992) on the basis of water required to maintain an adequate quality of life, a country or area whose renewable freshwater availability drops to less than 1,700 cubic meters per person and year experiences water stress. Water scarcity, a condition in which chronic water shortages affect human and ecosystem health and hamper economic development, occurs when the renewable freshwater availability falls below 1,000 cubic meters per person per year.

Future water availability is a function of future supply and demand. Water supply is controlled by climate and water demand is driven by demographics and economic factors (Arnell 1999). Climate change has already effected changes in the global water cycle, and even larger changes are projected as global warming continues (IPCC 2001). Subtle shifts in mean temperature and precipitation have brought about important changes in the occurrence of extreme climate events. Deserts and desert margins are particularly vulnerable to soil moisture deficits resulting from droughts, which have increased in severity in recent decades and are projected to become even more intense and frequent in the future. Conversely, flood events are predicted to be fewer but more intense, in which case little moisture would infiltrate into soils and runoff and eroded sediment would concentrate in depressions, reinforcing the patchiness of the desert ecosystem.

Climate change affects less the total amount of available water and more the overall water regime and the timing of water availability in deserts – particularly deserts whose water supply is currently provided by melting snow or ice (see above). Thus, a large fraction of the water used for agricultural and domestic purposes in the arid Southwest of the United States, the deserts of Central Asia, and the Atacama and Puna Deserts on both sides of the Andes is drawn from rivers that originate in glaciated/snow-covered mountains. As the volume of snowpack that is accumulated annually diminishes, river regimes change from glacial to glacio-pluvial and then to pluvial. As a result, total runoff is expected to increase as the glaciers begin to melt and then to decrease as the total area covered by snow and ice declines (see box 6.3 for the Himalayas and Yao and others 2004). Annual turnover accelerates. Peak discharges will shift from the summer months, when the demand is highest, to the spring and winter, with potentially severe implications for agriculture. Climate and streamflow scenarios estimate that California's irrigated farmlands are likely to lose more than 15 per cent of their value because of losses in snowpack (Service 2004).

Water demand of the natural environment is likely to grow as potential evaporation increases as a result of warming. Increases in potential evaporation are projected to reach 7.5 – 10 per cent by 2020 and 13 – 18 per cent by 2050, depending on the global scenario that is used (Arnell 1999). A more important factor in the increase in water demand in deserts, which is harder to quantify, is their growing population and its aspirations for an improved standard of living. Water demand will increase rapidly in some desert areas, particularly the expanding urban areas, and only moderately in others. However, water-use-per-person has been rising less rapidly than previously predicted and is actually declining in a few parts of the world thanks to improvements in water-use efficiency in the agricultural, municipal, and industrial sectors. Despite this positive development, there is concern about whether improvements in water use efficiency will keep pace with the projected growth in population (Gleick 2001).

Due to a shortage of surface water resources, many desert countries rely heavily on the exploitation of groundwater. For example groundwater currently provides for 95 per cent of Libya's freshwater needs and 60 per cent of Algeria's (UNEP 2002). Most deep groundwater extracted in deserts was put in place thousands of years ago under wetter climatic conditions during the Pleistocene and is considered non-renewable on a human timescale. With the number of deep wells increasing exponentially in many areas, groundwater has been extracted at a large scale over the past five decades. While some reserves are estimated to be vast and likely to last for a long time at current rates of exploitation, others are being depleted rapidly and are already experiencing declines in water levels and water quality (Moench 2004).

Quantification of groundwater resources is extremely complex, particularly in the absence of reliable information on groundwater extraction. The only systematic global scale groundwater survey was compiled by the United Nations (United Nations 1983-1990) and has not been updated since. The lack of precise information on groundwater availability and recharge rates poses a major challenge to sustainable management of the resource. Problems of groundwater exploitation have become more acute and more widespread under the pressures of population growth and urbanization, exacerbated by a growing competition between sectors (Vörösmarty and others 2000). Demands on water by municipal and industrial uses are expected to increase at the expense of irrigated agriculture; for example, water transfers from agricultural regions previously supported by Colorado River water have already become a common means of addressing water shortages in urban southern California (Johns 2003).

In addition to the limited quantity of water resources available in deserts, deterioration of their quality is another concern. Because of their dependence on dwindling water resources, societies in deserts are particularly vulnerable to the effects of water pollution, which threaten human and livestock health and socio-economic development. The deterioration of both surface and groundwater resources by agrochemicals, mostly pesticides and fertilizers used in irrigated agriculture and the salinity of return flow, is likely to increase in the future, if the expansion of irrigated lands continues without any significant improvements in drainage and treatment of agricultural wastewater. Groundwater quality often deteriorates where extraction levels are high – and they are projected to increase, particularly in fast-growing urban areas – because of the inflow of more saline deep groundwater or sea water in coastal desert areas. Future sea-water intrusion into groundwater may also be caused by sea level rises resulting from global warming (IPCC 2001).

Worst case scenario	**Best case scenario**
• severe water depletion and degradation • potential conflict over water resources among users • extremely high costs of supply • water used for low value purposes	• clean unpolluted water • equitable access to water • water allocated and used efficiently • irrigation of only high value and strategic crops

Biodiversity

Global biodiversity is changing at an unprecedented rate under the influence of population growth and land use changes (Jenkins 2003). Deserts used to be considered as areas of limited interest for biodiversity, but this perception is changing as research finds them to be the home of unique species and genetic adaptations (IPED 1994). Genetic and species diversity are threatened by the extinction of native species and the deliberate and not-so-deliberate introduction of non-native species, which have unintended and often damaging consequences for the ecosystem.

Although declines in biodiversity are an important aspect of global change, which have significant implications for the ecosystem and the natural resources, scenarios of biodiversity are rarely found and are less authoritative than scenarios for greenhouse gas emissions and climate scenarios. Sala and others (2000) developed global biodiversity scenarios based on the estimated impacts of five driving forces on different biome types. Deserts were estimated to be experience only moderately change in biodiversity, with maximum projected changes of 60 per cent. While land use emerged as the dominant driver of change in desert biodiversity, deserts were also moderately sensitive to increases in atmospheric CO_2 and slight changes in precipitation and temperature, which could shift the proportion between C_3 and C_4 species (Melillo 1999, Alward and others 1999). Claussen and others (2003) modelled an expansion of grassland into the Sahara, which is theoretically possible under conditions of steady increases in CO_2 concentrations and summer precipitation.

Scenarios of biodiversity are extremely difficult to quantify, as uncertainties in the projected changes of each of the driving forces are amplified. The nature and strength of interactions among the driving forces are poorly known. Non-linear developments, such as the introduction of invasive species, add to the uncertainties. Sala and others (2000) therefore presented three alternative scenarios, assuming (1) no interaction among the drivers of change, (2) antagonistic interactions (as when changes in biodiversity are determined by the factor that has the greatest impact) and (3) synergistic interactions (as when drivers amplify one another). While these scenario had very different outcomes for other biomes, deserts showed almost equally little change in all three scenarios. In desert hot spots of biodiversity, such as the riparian areas that are particularly affected by development, larger biodiversity losses are expected.

Worst case scenario	**Best case scenario**
• loss of natural wetlands • rapid rates of biodiversity loss • increased vulnerability to drought and a result of biodiversity loss	• healthy natural wetlands • diminished rates of biodiversity loss • extended and well-managed protected areas network

Land degradation

Land degradation is arguably one of the major global environmental challenges. Although its precise definition has stirred debate – even more so in the definition of desertification – land degradation occupies a prominent place in major environmental conventions and initiatives (among them the United Nations Convention on Environment and Development, the United Nations Convention to Combat Desertification, the World Summit for Sustainable Development, and the Millennium Ecosystem Assessment). In one of the more authoritative definitions, the UNCCD defines land degradation as "the reduction or loss of the biological and economic productivity and complexity of terrestrial ecosystems, including soils, vegetation, other biota, and the ecological, biogeochemical and hydrological processes that operate therein … resulting from various factors including climatic variations and human activities" (UNCCD 1994: p. 5).

Deserts in the strict sense are less susceptible to land degradation than other ecosystems for two reasons: (1) their biological productivity is very low; and (2) vast desert areas are almost devoid of human population, and human impact. However, desert margins, oases and irrigated lands within deserts, have a higher biological potential and are subject to increasing population pressure, and thus tend to constitute potential hotspots of degradation.

As a creeping environmental problem with low-grade, incremental changes over time (Glantz 1994), land degradation is difficult to measure with any level of precision and this is one explanation of the widely diverging estimates of the extent and severity of the problem. The Global Assessment of the Status of Human-Induced Soil Degradation (GLASOD), commissioned by UNEP in 1988 as the first comprehensive soil degradation overview at global scale, estimated the extent of highly to very highly degraded soil in deserts to be around nine per cent - which is considerably less than in the semiarid drylands. Other studies maintain that degradation is not as prevalent a phenomenon in drylands as suggested by many global-scale assessments, which often suffered from subjectivity, poorly representative ground data and poor resolution. Rather, degradation seems to be concentrated in specific locations, such as around settlements and boreholes (see for example: Warren 2002).

In oases, soil salinization and the encroachment of sand dunes are major problems. Soil salinization occurs in two ways: (1) intrusion of saline seawater into deep coastal aquifers – such as the decline of oases on the coastal plain of Batinah in Oman (Stanger 1985) – a rather minor issue, though, on the global scale, but locally significant; and (2) evaporation of excess irrigation water, often associated with poor soil drainage, that leaves dissolved salts in the soil – a widespread problem in deserts globally. Sand dune encroachment into oases, a recurrent and normal phenomenon, can be exacerbated by degradation of the vegetation cover on surrounding pastures (resulting from prolonged drought or overgrazing), which exposes sandy soils to deflation. Along the Wadi Draa in southern Morocco, sand has moved into irrigation channels and palm groves (Corsale, 2005).

Given the difficulties in estimating the current status and extent of land degradation in deserts, making projections into the future is tricky. Land degradation is a complex phenomenon, which is affected by changes in a number of human and environmental factors, projections of which are themselves error-prone: population numbers, resource demand, climate, trade and technology, and political/institutional factors being foremost among them. Furthermore, we have only incomplete knowledge about ecological thresholds to degradation and recovery potential of once degraded lands, which vary depending on their soil and geomorphic age (Brown 2000).

Few studies have offered a future outlook for land degradation. One is the "2020 Vision for Food, Agriculture and the Environment", an ongoing initiative by the International Food Policy Research Institute (IFPRI) aimed at developing a shared vision on how to meet future world food needs while reducing poverty and protecting the environment. The report expects a reduced expansion of irrigated area by the year 2020, and increased investment in drainage to deal with salinization. Nevertheless, they believe that problems of salinization will increase, as irrigation systems with inadequate drainage continue to age. Potential hot spots for this kind of soil degradation in deserts include the Nile delta, the Indus, Tigris and Euphrates alluvial lands and parts of northern Mexico (Scherr 1999). On the other hand, a considerable amount of unsustainable irrigated land is projected to go out of production and new opportunities for rehabilitation of degraded lands and sustainable pasture management systems are expected to be developed for them.

Worst case scenario	Best case scenario
• increasing erosion, deflation and salinization • reduced livelihood and economic development options • unequal access to land and escalating poverty	• declining rates of land degradation • rehabilitation of degraded lands • optimal livelihood and economic development options • equitable access to land and appropriate tenure over natural resources

Desired outcomes of action

The future of our deserts, as natural and cultural landscapes, depends on our ability to develop their potential as providers of goods and services without degrading their ecological value in the face of increasing human pressures and possible climatic deterioration. Desired outcomes of action can be subsumed under two closely related concepts – human well-being and environmental sustainability.

The Millennium Ecosystem Assessment defines human well-being on the basis of five dimensions: the provision of the basic materials needed to sustain life, freedom and choice, health, good social relations, and personal security (MEA 2003). Human well-being in deserts is generally below the global average. With the exception of the American Southwest and parts of the Arabian Peninsula, desert regions are characterized by comparatively high infant mortality rates and low economic performance, as expressed in their per capita gross domestic product (MEA 2006). Not surprisingly, livelihood options in deserts are limited primarily by the scarcity of water, which, when coupled with poor infrastructure and social and political marginalization, negatively affects health and food security.

Environmental sustainability is a concept that emerged as part of the sustainable development discussion triggered by the World Commission on Environment and Development (1987). It implies safeguarding environmental goods and services, or at least not depleting them (Goodland 1995) and is compatible with qualitative improvements in human well-being rather than quantitative growth in production and consumption – particularly in deserts, given the heavy resource consumption of all desert development and the vulnerability of those resources.

The nature of human-environment interactions differs among and within societies in deserts, and consequently so do the options for action. The poor are particularly vulnerable to resource shortages or degradation, because their daily lives closely rely on their immediate environment. The better-off are better insulated from the variable environment and thus hardly feel the effects of a drought. Importation of water and goods at affordable prices, as in Australia, Arabia or the American Southwest, can temporarily isolate the challenges of living in a desert, and diminish our awareness of limits and sustainability. Although they engage in the least sustainable rates of resource consumption, prosperous societies have (theoretically) the most options available to them to address environmental problems. However, there appear to be insufficient economic, social or ethical incentives to pursue a sustainable path, at least to this point.

Options for action

In the face of globally increasing resource shortages, deserts hold a unique position with respect to the key resources of water and energy. Because water is in such short supply, deserts are the first environments to be forced to deal with water shortages. They should be in the forefront in developing and testing water-efficient technologies and policies, which are likely soon to become globally relevant as water demand increases worldwide. Energy might hold be another opportunity for development in deserts, because of the implications of the increasing scarcity of fossil resources and the impact of their use on the global climate hold for society. More emphasis will have to be placed on renewable energy (solar, wind, geothermal) in our energy portfolio. The low cost of land and the abundance of solar energy should offer deserts an advantage on which they might capitalize.

Resource management for desert ecosystems

The pulse-reserve character of desert ecosystems presents particular challenges to sustainable resource management. While the notion of sustainability implies some sort of balance between resource provision and extraction, the extreme variability inherent in desert ecosystem tends toward boom-and-bust cycles rather than a steady flow of environmental goods and services. As a result, sustainability is difficult to define for desert ecosystems and can certainly not be achieved by prescribing a fixed carrying capacity (such as, number of livestock that a particular region can sustain) (Behnke and Scoones 1993).

Mobile, extensive forms of grazing have been found to be well adapted to the variable resource availability in desert ecosystems (Niamir-Fuller 1999). Traditional users have learned sustainably to exploit ecosystem cycles through mobility and regulation to control rangeland use (as in the collective reserve Hema system in Arabia). In contrast, modern trends toward the sedentarization of pastoralists and the provision of subsidized supplemental animal feed, though implemented in the interest of economic sustainability, increase pressures on the ecosystem by allowing for long periods of stay (Al-Rowaily 1999).

Sustainable resource management policies must respond to the pulse-reserve character of the desert ecosystem by supporting mobile or otherwise flexible systems which can respond to the variable and unpredictable desert environment and still remain economically viable over long periods of time. This support can take the form of providing mobile services (medical care, schooling), encouraging risk spreading through common property management (Hesse and Trench 2000), and providing timely and accurate information about the state of pastures.

Mitigating the “bust” part of the cycle is another important component of the sustainable management of desert ecosystems. This includes not only emergency support during drought crises, but also proactive management to increase human and societal resilience, by creating diverse rural income opportunities, providing support for animal marketing, providing credit, and establishing other forms of insurance that can sustain rural livelihoods during times of stress. An alternative is to encourage urbanization that essentially removes pressures on rural natural resources (Portnov and Safriel 2004).

Making use of modern technology

Traditional wisdom on coping with drought (Mortimore 1998) complemented by cutting-edge science and information technology (for example drought forecasting and climate change scenarios), holds great potential for sustainable resource management. If we can have better information about the near future, we can plan better how to deal with it.

Although drought alone cannot be held responsible for causing food insecurity (Sen 1981), some desert regions face food insecurity and increases in excess mortality during prolonged drought periods. USAID has initiated a famine early warning system project (FEWS NET: http://www.fews.net/), which provides drought early warning and vulnerability information for drought-menaced African countries, both in semiarid drylands and in deserts.

The objectives of interventions triggered by the early-warning information range from saving lives in response to immediate emergencies (for example, emergency food programs and livestock health interventions), to saving both lives and livelihoods by reducing exposure to risk by developing diverse opportunities to generate income (such as, crafts and other off-farm employment), other than agriculture.

While the activities of FEWS NET tend to focus on the most vulnerable human populations, an example from a more robust setting is the Rangeview project (http://rangeview.arizona.edu), that sprang from an initiative to make geospatial technology accessible to a range of users. Launched in 2000 to provide rangeland managers in the American Southwest with satellite-derived information about status and trends of vegetation greenness, it evolved into a decision-support tool and has meanwhile been extended to cover the entire United States. Similar initiatives, making use of the internet as a cheap means of information exchange, could be beneficial to rangeland management in desert regions around the world.

This type of tool helps natural resource managers to understand what is happening now and compare it with what has been happening over time come to an appreciation of where we are at any point in time. As our ability to understand and model the global climate system improves, we are able to develop increasingly useful seasonal weather forecasts for large regions and long term scenarios, which can be exploited for adaptation planning to climate variability and change, which are inevitable during the next decades (Dessai and others 2005).

Technical knowledge and reliable forecasts alone, however, are insufficient, but need to be implemented to the benefit of the people under a given set of circumstances. Climate change adaptation planning therefore must include the identification of vulnerable population groups and exploration of effective and affordable livelihood strategies during times of climatic stress. Perhaps most importantly, there need to be systems in place that have the political will and institutional capacity to act on the most likely scenarios, or at least to accommodate some outcomes.

Renewable energy from the desert

The provision of clean and affordable energy is one of the most critical problems that confront human development. The current world energy system is dominated by fossil fuels and will fall short in meeting the energy demands of a projected world population of 10 billion by the mid of the century (Smalley 2005). In prosperous nations energy conservation through improved efficiency offers one possibility to reduce demand. In much of the developing world, however, conservation is meaningless because little energy is currently used and their total demand can only increase as they develop. Although currently not yet profitable, renewable energy resources could account for a third to a half of the global energy supply by 2050, based on price competition (Shell International 2001).

Their continuously high solar radiation makes deserts ideal locations for both small decentralized units and large solar cell installations, the potential reach of which is not limited to deserts. Apart from technological feasibility, the adoption of solar energy as an alternative to fossil fuels depends on the global as well as national policy environments and concrete implementation strategies. Possible incentives to encourage the shift towards renewable energy sources include taxes on pollution generating practices, such as the burning of fossil fuels, while providing loans, grants or subsidies for the use of solar and other renewable energy resources. In addition, allocating funds for relevant technological research and training and for marketing of solar technologies and raising public awareness of renewable resources as a clean alternative to fossil fuels could be used to help promote the use of solar energy.

“Soft path” for water development

Twentieth-century water policies were largely dominated by the construction of massive water extraction, storage and transport infrastructure, which brought benefits, such as the expansion of irrigated agriculture in deserts, but at substantial environmental cost (Gleick, 2003), as illustrated by the examples of the Aral Basin in Central Asia and the Imperial Valley in the Southwestern United States.

In analogy to the “soft path” for energy policy advocated by Lovins (1976), leading water experts strongly promote a “soft path” for water development in response to the impending global water problems (Gleick 2003; Rijsberman 2004). This soft path should focus on water-use efficiency and the control of demand rather than building ever bigger dams and endlessly developing new sources of water. Deserts, as the first environments confronted with water shortages and forced to rethink water use priorities, should be among the forerunners in developing and testing innovative, and globally relevant, technologies and policies.

The implementation of water conservation measures and improvements in water use efficiencies needs to be supported by economic and institutional structures. In many desert regions, water prices currently do not reflect the value of water. A strategy to discourage wasteful water consumption, which at the same time contributes to more equitable access to water, is to support low-income and low-volume users with transparent subsidies, financed by excessive water consumers. Raising public awareness about the need to conserve water is particularly important for new migrants into deserts who have not developed a "sense of place", such as those moving into the desert cities of the American Southwest.

Small-scale decentralized water supply facilities and the involvement of communities in the decision-making process about water management, allocation and use ensure more equitable access to water and potentially lower environmental impacts than the massive centrally-planned water schemes of the 20th century (Gleick 2003). In the communal parts of Namibia, for example, water point committees have been set up as part of a larger decentralization policy, which are responsible of the provision of water to the community and the maintenance of communal water installations (Werner 2000).

Promotion of only high value-added uses of water can improve water efficiency: for example, the high-tech industrial sector enhances the value of each cubic meter of water used many times more than the agricultural sector (Gleick 2001). Within the agricultural sector, one possibility to improve water efficiency is to restrict irrigated agriculture in deserts to high value crops (for example, dates) or aquaculture, whereas lower value crops (for example, maize) can be imported from regions better endowed with water. Despite the risks involved with abandoning their food independence, many water-poor countries already choose to import food rather than growing it, creating a virtual flow of water, which is contained in the imported food products or other commodities that require high water inputs. With increasing globalization, the import of "virtual water" becomes a tool in water-resource management, which can be used to relieve pressure on scarce water resources in deserts.

Conclusions

What will the future hold for the deserts of the world? Deserts are and will remain constrained in their productive potential by their particular nature: the widely varying conditions of the desert ecosystem, the scarcity of water, and the oscillating resource variability.

Global climate change, coupled with increased population pressure, particularly in the desert margins, montane areas and wetlands, is likely to affect the more productive desert areas and pose some new and significant threats to biodiversity and sensitive endemic species. The hyper-arid core deserts, by contrast, are going to be less affected by mounting pressures on their fragile biological resources. However, water depletion and salinization of irrigated agricultural soils are likely to continue as two of the main environmental problems in many deserts, encouraged by modern technologies for groundwater prospecting and pumping. A sort of modern itinerant agriculture has already emerged, where large barren areas of salinized agricultural soils are left behind as groundwater resources become exhausted and agricultural operations move on to new lands.

These predictions, however, are not fixed and unchangeable. The scenario analyses discussed in the previous sections show that there is a wide range of possible outcomes for deserts, an array of alternative futures. Whether our deserts will follow a path of intensive development, industrial-scale agriculture projects and mega-cities attracting massive immigration – a vision that has been called, somewhat sarcastically, the "Cadillac Desert" (Reisner 1986) – or an alternative path of sustainable development, spurred by a "sense of place" and prioritizing the desert environment and the traditional culture of local communities, is largely determined by our common visions and collective action taken to fulfill them.

In reality, current development in many deserts seems to suffer from a lack of vision altogether. Few, if any, coordinated programs exist for either development or conservation of the land. The unique values and limitations of the desert are rarely acknowledged. Development schemes, such as programs for irrigated agriculture or mass tourism, tend to spring up haphazardly with no attempt to coordinate them or to plan for their long-term sustainability. Immigration to the desert is often random and opportunity-driven, and new settlements sprawl over valuable landscapes and create problems for water supply and waste management. Without proper planning and a vision of sustainability, traditional life-styles atrophy and indigenous knowledge are lost, victims of short term, ephemeral economic projects.

Quite clearly, a continuation of the energy- and water-intensive development model (the "Cadillac Desert") will lead to even more severe water depletion and degradation than is observed today, followed by potential conflict over water resources among users, escalating costs of supply, and, paradoxically, the continuation of a non-renewable model in which water, often under immense subsidies, is used for low value purposes. On the other extreme end, increased isolationism with exclusive reliance on traditional knowledge runs the risk of losing access to new sustainable technologies and might lead to diminished opportunities for younger generations and eventually reduced livelihood and economic development options.

A new, more balanced vision is needed, where deserts and their inhabitants are valued by governments and an educated civil society; where sustainability and the well-being of desert people is given highest priority; where desert development is guided by a long planning horizon and based on an acute understanding of the limitations and potential of these very unique environments; and where market forces are harnessed to promote a desert-compatible development such as low impact services or high-technology development.

The active participation of as many community groups as possible in the development of a common vision for a particular desert is a prerequisite for the successful formulation and implementation of policies towards realizing this vision. The challenge remains to harness not only local, but also global policy and market mechanisms to work for a sustainable future of our deserts, where a viable balance between protection of the environment and economic development opportunities is achieved.

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